AD

GRANT NUMBER DAMD17-94-J-4502

TITLE: Surgical Robot Hand

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REPORT DATE: January 1998

TYPE OF REPORT: Final

PREPARED FOR: Commander
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

19980831 014

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1998	Final (23 Sep 94 - 31 Dec 97)

4. TITLE AND SUBTITLE

Surgical Robot Hand

5. FUNDING NUMBERS

DAMD17-94-J-4502

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Daum GmbH
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Accompanying Video Cassette

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

It has been demonstrated that a small robotic hand working with Bowden pulleys and SME shape memory elements is possible below the range of 10 mm in diameter and movement of nearly 3 Hz speed. The robot hand can be sterilized and used for medical applications and can easily carry up to 400 g of weight. It can be made adaptable to different software and electronic systems and can be pushed through standard surgical trocars. Time delays are still in the acceptable range. Such a robot hand can be controlled by means of a dataglove. It has been demonstrated that a dataglove can easily be manufactured with resistive rubber. Time delay of that resistive rubber is still five times longer than time delay of robotic hand. Both together, robotic hand and dataglove comprise a total time-delay which should be acceptable for standard surgical procedures. Robot Hand with dataglove is precise in the range of a fifth of a millimeter. We propose to test the robot hand now on different surgical robotic systems.

14. SUBJECT TERMS

robotic hand, dataglove, controlling of robotic hand with dataglove, telesurgery, telemanipulation, minimally-invasive surgery

15. NUMBER OF PAGES

184

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

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March 25, 1998

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CONTENTS

1. INTRODUCTION

In the overall program telesurgery we were to build a surgical robot hand which can be moved remotely. The goal was to make a small handalike structure, suitable to be moved through a surgical trocar of 12 mm inner diameter. We added ourselves and developed a dataglove as a tool to control the robot hand. This report is structured in the following sections:

- Mechanical explanation to give the reader a perspective on the construction and the materials used in the robot hand.
- Electrical and software explanation to give the reader a perspective on the controlling mechanism of the robot hand.
- Explanation of dataglove to the robot hand, which also can be used for other technical appliances.
- System explanation and first results of working prototype.
- The report ends with the financial and patent statement.
- A video is attached to demonstrate the robot hand with dataglove.

The program was originally granted to Daum GmbH, a legal entity of the country Germany. During the periode of the grant we moved to the USA and finished our project in our office in Baltimore, Maryland.

2. SUMMARY

The object of the project was to build a robot hand, which can be inserted via a surgical trocar into the human body of the patient. It shall be used for general remote control manipulation during endoscopic surgery.

We used different mechanism to drive the robot hand. One achievement was the use of electrical motors on cables and pulleys, the other was to use shape memory alloy elements (sme). Both mechanisms are presented herein. We still use sme as driving actuators but use them in a different way as proposed.

3. MECHANICAL ACHIVEMENTS OF THE ROBOT HAND

The surgical robot hand has been built. Diameter is 11 mm, which can be pushed through a 12 mm trocar for minimally invasive surgery. It comprises two fingers and one thumb with one wrist and a total of 7 degrees of freedom (7 DOF). Electronics had to be built to control the hand and a driving unit was built to drive the fingers. Not included in the original contract but also developed was a dataglove to control the robot hand. Results of the robot hand are shown in the video which is attached to this report.

We developed the DataGlove because we found out that we cannot control the robotic hand by joysticks or other virtual reality means which are on the market so far. The movement of the hand is so complexe that the Dataglove is the only tool to control a Robot Hand. Since all other DataGlove concepts are too stiff and too heavy we had to design our own system.

Robot hand can carry up to 250 gramms of weight, moves with speed of 2.6 Hz and can open up to 3 cm. All detailed drawings for the surgical hands and of electrical circuits are attached to this report in appendix I. An overview of the robot hand is shown in drawing 3.a.1. It can be seen that the hand comprises two fingers and one thumb and a wrist. Drawings 3.a.2 to 3.a.6 show details of said fingers and wrist.

The robot hand has three fingers because most manipulations can secureley carried out with just three fingers. Each finger with two joints which can be moved independently of each other. Wrist of the robot hand can be moved up and down to 30 ° by a control system which operates Bowden cables.

The gear of the robot hand consists of six linear pulse motors for the finger movement which transform the rotation movement into a linear movement. For the movement of the wrist a bigger normal pulse motor is used.

Shells of so called Bowden cables for the fingers are connected with the gear, and the core assemblies are fixed on the shafts of the linear motors which permits the displacement of shell and core assembly one to the other. The wire cables of the wrist of the robot hand are connected mechanically. As a result, wrist of robot hand can be moved at a speed of about 1 Hz.

Distance sensors of robot hand (in this stage potentiometers) are fixed on the according connecting elements between core assembly of Bowden cable and linear pulse motor as well as between wire cable and pulse motor. Hence, movement of wrist and finger joints is controlled.

The following figures and drawings are used to describe the robot hand construction. These drawings and figures are found in the appendix I of this final report.

3.a Construction of Hand

Fig. 3.a.2

Finger II, 1 represents the second (distal) joint of the finger of the robot hand for grasping and handling. In drill hole (diameter 0.85 mm) is a dowel pin (diameter 0.8 mm) for movable fixation to finger II,2. The kinked core assembly of the Bowden cable is put into the small drill hole (diameter 0.5mm) in order to permit the movement of the finger.

Fig. 3.a.3.

Finger II, 2 represents the first (proximal) joint of the finger of the robot hand for clenching an object. Other medical devices can complete only a grasping movement, e.g. forceps.
The biggest drill hole (diameter 1.05 mm) with dowel pin (diameter 1.0 mm) serves as a movable fixation to joint 1. By means of middle drill hole (diameter 0.8 mm) finger II,1 is fixed. Core assembly of Bowden cable is put into the smallest drill hole (diameter 0.5 mm), pushed through it and bent. The shell of the Bowden cable for finger II,1 is layed into the groove and soldered.

Fig. 3.a.4

Joint 1 is the first part of wrist of robot hand. By means of said wrist it is possible to grasp or move objects which are situated at another as the longitudinal axis of the trocar tube.
The biggest drill hole (diameter 2 mm) is the pivot of the wrist. By two fixing pins (diameter 2 mm) disk is fixed and fastened at joint 2. At the two drill holes (diameter 1.0) the three fingers II, 2 are fixed. Hereby, the two outer fingers (index and middle finger) are fixed on that side of joint 1 on which only one longitudinal groove is situated. Wire cable for movement of wrist is passed through drill hole pair (diameter 0.7 mm visible in enlargement X) . Wire cable is soldered with joint 1 in the groove (breadth 1 mm). Shells of the Bowden cables for the three fingers II,2 are put and soldered in the three grooves (breadth 1.3 mm).

Fig. 3.a.5

Disk serves for movement of wrist of robot hand. Wire cable is rolled around the disk in the radius (0.3 mm) in order to move joint 2.

Fig. 3.a.6

Joint 2 is the second part of wrist of robot hand. Wire cable for the wrist is passed through the laterally arranged drill hole pair (diameter 0.7) and guided to the enveloping tube. Enveloping tube is put onto the shoulder (diameter 10 mm) and soldered there. Groove (breadth 1 mm) running around the shoulder shall be used later for a small protective glove out of silicon in order to prevent contaminations of device and infection of patient. Disk is placed on the right side of the small web. Surface of the right web is bigger than of the left. In that way, supporting surface of the disk is as big as possible. Hereby, good guidance of the cable wire is achieved. Bowden cables coming from the enveloping tube are passed through joint 2 and guided to joint 1 and to the fingers II1, and II, 2.

3.b Construction of gear of robot hand

Fig. 3.b.1

Fig. 3.b.1 shows an overview of the motor-unit of the robot hand device. Numbers refer to figures described in the text below.

Fig. 3.b.2

Flange part of motor is used in the gear of robot hand for taking up the linear movement of the according motor and to transmit it over the soldered core assembly of Bowden cable to the according finger joint. This flange is the connecting part between motors and core assembly of Bowden cable. It is also the connection to the sliding potentiometers.

Motor shaft (diameter 0.51 mm) of linear pulse motors is pushed through the longitudinal drill hole (diameter 3.51 mm) and fixed in the screw thread by a setscrew. Slide of the according potentiometer is put into the big longitudinal groove (breadth 1 mm) and fixed with the motor shaft. In order to fix core assembly of Bowden cable the core is put into the small longitudinal groove (breadth 1 mm), positioned and soldered there.

Fig. 3.b.3

Shells of Bowden cables for the fingers of robot hand are situated in screw spindle and operated there by motor. Additionally, Bowden cables can be adjusted mechanically by the means of screw spindle. Ends of said shells are put through drill hole (diameter 1.5 mm) and soldered in the groove (length 5 mm). Key surface (breadth 4 mm) and nut (M 5) allow to adjust shell of Bowden cable and core assembly by nut for screw spindle.

Fig. 3.b.4

Nut of screw spindle is the second mechanical element for ajustment of Bowden cables. Nut together with screw spindle forms a rigid connection between gear for robot hand and Bowden cables.
Nut is put into the robot hand gear (2/4) and (3/4). Thrust washer is put into the groove (breadth 1.05 mm) in order to prevent movement of nut back and forth in longitudinal direction. In spite of this fixation in longitudinal direction the rotation of nut is possible because of the precise seat of elements. Key surface (10 mm) is used for adjustment of Bowden cables.

Hereby, screw spindle is held fast on its key surface in order to prevent torsion of Bowden cables and at the same time nut is turned. If adjustment is finished hexagon nut of the screw spindle is drawn up, hence connection is fixed.

Fig. 3.b.5 and 3.b.6

Gear (2/4) of the robot hand is the second part of the gear system. Three motors for the fingers are attached on it. Nuts for screw spindle are placed on the gear and gear connects the bigger elements of the complete gear system.

Motors are placed on three big drill holes (diameter 14.5 mm) and mounted on the screw threads (M 3) on the diameter 48, 49 on the left and right sides of the drill holes . A flat head bolt is placed in the drill hole of mounted base and drawn up.

Fig. 3.b.7

Gear (3/4) of the robot hand is the third part of the gear system. Three further motors for the fingers are attached there. In the same manner as on gear (2/4), there are situated the nuts for the screw spindle and the gear connects the bigger elements of the complete gear system as well.
Motors are placed on three big drill holes (diameter 14.5 mm) and mounted on the screw threads (M 3) on diameter 49, 48 on left and right sides of drill holes. A flat head bolt is placed in the drill hole of the mounted base and drawn up. Screw threads (M 3) on diameter 60.1 are used to mount the robot hand gear (2/4).Three nuts for screw threads are put into the three drill holes (diameter $10^{-0.05}$ mm) and fixed by thrust washer. Potentionmeters and printed cards can be fixed by means of the screw threads (M 3) on the milled surfaces.

Fig. 3.b.8

Gear (4/4) for robot hand is used for attachement of Isel pulse motor, which moves the wrist.

Gear (4/4) is connected with gear (3/4) by three pan head screws in the three drill holes (diameter 3.2 mm) situated on diameter 60. Motor is fixed on the quadratically arranged drill holes (diameter 3.2 mm).

Fig. 3.b.9

Distance sleeves are put between the three big elements of the robot hand gear system. These elements are connected by screws in the drill holes (diameter 3.4 mm).

Fig. 3.b.10 and Fig. 3.b.11

Tension block 1 and tension block 2 are important elements of the wrist mechanic. The ends of the wire cable for wrist movement are soldered in these two tension blocks. Their construction allows that wire cables can be moved one against the other. First wire cable is put into the groove (breadth 1 mm) and soldered.

Tension block is pushed with fits (diameter 4 mm) onto the sliding rods. Screwed shaft is screwed into tension block. By rotation of screwed shaft tension block moves linearly.

Second wire cable is put into the groove (breadth 1 mm) and soldered. Tension block is pushed with the fits (diameter 4 mm) onto the sliding rods. Screwed shaft is screwed into tension block. By rotation of screwed shaft tension block moves linearly. Geometry of tension block 2 is different from geometry of tension block in order to prevent an impediment of the wire cables.

Fig. 3.b.12

Connecting element between gear of robot hand (1/4) and gear of robot hand (2/4) is the distance plate which is also used as base plate for the wrist mechanic.
Bowden cables are layed from outside into the slots (breadth 2 mm) of the distance plate. For connection of robot hand gear (1/4) and (2/4) are used the six drill holes (diameter 4.3 mm) arranged on diameter 60. A ball bearing is put into the drill hole (diameter 12.99 mm) in order to allow a light work of screwed shaft. Into the drill hole pair (diameter 3.2 mm) are put sliding rods which are fixed and drawn at the back side by screw nuts.

Fig. 3.b.13

Gear of robot hand (1/4) represents the connection between the other gear elements and the enveloping tube of robot hand. Enveloping tube is pushed into the drill hole (diameter $11^{+0.1}$) in the middle of the flange which is squeezed by four screws (M3). Screwed rods are driven into the drill holes arranged on the inner site. Three drill holes in outer surface are used for fixation of housing (aluminium tube, diameter 80).

Fig. 3.b.14

Screwed rods serve as connection and distance parts between gear of robot hand (1/4) and distance plate.

Short screw threads are driven into the gear of robot hand (1/4). Distance plate is put onto the long screw threads and screwed down at the back side.

Fig. 3.b.15

Two sliding rods serve as guidance for the tension blocks. Screw thread is pushed into the distance plate and screwed down at the back side. The tension blocks slide on the fit (diameter 4 mm).

Fig. 3.b.16

Screwed shaft permits the movement of the wrist. Rotation movement of motor is transformed into a linear movement by tension blocks. Tension block 2 is screwed onto the right-hand thread (M 6x0.5 RH), and after that tension block is screwed onto the left-hand thread (M5x0.5LH). If screwed thread rotates the tension blocks moves either one away from the other or one toward the other in dependance from the direction of rotation. In that way it is possible to achieve a uniform movement of the wire cables and the wrist. Onto the left thread (M6) is screwed a nut for longitudinal fixation of screwed shaft and for tension of wire cables. The screwed thread is put with its fit (diameter 6 mm) into the ball bearing of distance plat.

Fig. 3.b.17 and 3.b.18

Connecting element and connecting element 2 are mounted for transmission of rotation movement of motor (Isel) . A tube (diameter 5 mm) is placed and soldered on its ends between these connecting elements. In that manner a shaft is formed. This shaft is pushed through the drill holes (diameter 10) which are situated at the gears (2/4) and (3/4) of robot hand and the rotation movement is transmitted almost right through the complete robot hand. The narrow web (breadth 3 mm) is put into the slot of the screwed shaft and drawn up by a nut (M2). Tube is pushed onto the cylinder (diameter 4 mm) and soldered with the connecting element. Connecting element 2 is soldered with the tube by the small cylinder (diameter 4 mm). Motor shaft of motor Isel is pushed through the drill hole (diameter 5.0 mm) and fixed by a setscrew.

3.c Shape-Memory Construction

The first test was to make a robotic hand made out of shape-memory elements. We first had to test those shape memory elements. To make a first finger tweezer we made various experiments and measurements of NiTi and CuZnAl shape memory alloys. We will explain the origins for results and observations in the following.

<u>Tested material samples</u>

Material samples are specified as shown below. Specifications are based on producer's information (Raychem Corp., California).

<u>NiTi compression springs</u>

This compression springs exhibit a one-way shape memory.

transformation temperature	between 50 ° and 70 ° C
diameter of wire	0.75 mm
external diameter of spring	5.80 mm
lenght of wire (cold)	4.50 mm
lenght of wire (warm)	19.00 mm
number of turns (active)	5
recommended strain by calefaction	5.0 N
recommended strain by refrigeration	2.5 N

(exceeding of recommended strains is disadvantagous to life-span)

<u>CuZnAl bending elements</u>

Bending elements exhibit a two-way shape memory .

transformation temperature	As ≈ 65 ° C	Af ≈ 80 ° C
	Ms ≈ 65 ° C	Mf ≈ 55 ° C
total lenght	40.0 mm	
clamping lenght	6.0 mm	
free lenght	34.0 mm	
thickness	0.80 mm	
breadth	8.0 mm	
recommended strain on free end	1 N	
way on free end	10.0 mm	

(exceeding of recommended strains is disadvantagous to life-span)

Temperature-way-characteristics

Measurements described below should determine exactly the course of the temperature-way-characteristic of shape-memory samples. In the same way producer's data could be reviewed. All characteristics indicated in various literature are certainly considerably idealized.

The experiment was arranged on the following way. Arithmetic paper was glued on the bottom of a level vessel. Samples were clamped with one side in a small fixture and put on the bottom of said vessel. Then the vessel was filled up with water so that the samples were covered and put on a hot-plate. In this way, constant heating and cooling of the samples are granted and considerable abrupt variations in temperature are avoided. Water was heated and cooled while permanently stiring up it so that differences in temperature inside the vessel are as small as possible. Temperature was controlled by a digital thermometer.

In this manner, certain temperatures were related to certain lenghts of way, which were covered by the samples because of shape change. All temperature-way-characteristics of this report were done with this method. At the start- and endpoints of all characteristics we found relatively big measurement errors because at these points it is difficult to perceive, in which points of temperature a change of way begins or ends.

Hysteresis of CuZnAl bending elements

CuZnAl bending elements show a two-way shape memory. Temperature-way-characteristic can be considered as hysteresis. Characteristics in figures 3.c.1 to 3.c.4 show the results of each series of measurement. In figure 3.c.5 all this characteristics are shown on one page in order to have the possibility to compare them. Figure 3.c.5 shows that no certain temperature can be related to a certain way.

For the measurements in figures 3.c.1 and 3.c.2 one and the same sample was used. In figure 3.c.1 the characteristic of the bending element after a "longer" storage was taken during the first thermal cycle. Characteristic of figure 3.c.2 was taken a short time later during the second thermal cycle. For the characteristics in figures 3.c.3 and 3.c.4 we used other samples, but they were subject to a thermal cycle a short time before.

Interpretation:

In figures 3.c.1 and 3.c.2, the hysteresises are different. Temperatures of starting and end points are in figure 3.c.1 considerably higher. Besides, the hysteresis there is enlarged. But the characteristic was taken with the same sample. The arrangement of the experiment can be supposed as origin of this difference. The only difference in the arrangement of these experiments consists in that the characteristic of figure 3.c.1 was taken after "longer" storage during first thermal cycle, characteristic in figure 3.c.2 during the second.

It can be assumed that shape memory alloys forget their shape memory after longer storage. During heating, they remember their learned shape effect only by considerable high temperatures. The enlargement of the hysteresis in figure 3.c.1 can be explained by this inertia. The tested bending element of figure 3.c.2 shows an elongation of only 9 mm instead of 10 mm as indicated by producer. It can be expected that the shape memory of this sample was not optimal and for this reason the total possible shape change could not be achieved.

In figures 3.c.2 to 3.c.4 following average transformation temperatures were determined:

As ≈ 62 ° C	Af ≈ 81 ° C
Ms ≈ 76 ° C	Mf ≈ 54 ° C

If this transformation temperatures are compared with producer's data, divergences can be observed. Origin of this divergences could be reading errors, which can occur just by starting and finish temperatures.

Bending elements exhibits the biggest shape change per degree Kelvin in heating phase by 75 ° C with 4-7 mm elongation and in cooling phase by 67 °C with 5-6 mm elongation (determined in figures 3.c.2 - 3.c.4).

Characteristics of NiTi compression springs (compressed)

For compression springs it is necessary to define a initial (zero) position in order to give a correct interpretation of characteristics. As initial (zero) position is defined the position of the NiTi springs when heating is started. Because these NiTi springs exhibit a one-way shape memory, there is no shape change by following cooling. These springs can be compressed and stretched in "cold" state by external forces. They keep their forced state until they will be heated and then initial position will be achieved.

In our experiment the NiTi springs were compressed in cold state and the elongation is indicated in the characteristic as negative value. While heating the initial position is obtained. Figures 3.c.6 -3.c.9 show the separate characteristics of various NiTi springs. In figure 3.c.10 they are shown side by side for better comparison of values.

Characteristics of NiTi compression springs (stretched)

Here is defined the same initial position of the compression springs as described. In cold state, the springs are stretched before heating begins. Elongation is indicated as positive value. While heating, the initial position is obtained. Temperature-way-characteristic of compressed NiTi compression spring is shown in figure 3.c.6 to 3.c.9 and combined in figure 3.c.10.

These springs can be easily stretched, but compressed only until the point that one turn touches the other. In figures 3.c.11 - 3.c.14 are shown the separate characteristics of various NiTi springs. Figure 3.c.15 shows the characteristics on one page for better comparison.

NiTi can be for a two-way movement. Temperature-way-characteristic of NiTi compression spring material is shown in figure 3.c.16 to 3.c.20 and combined in 3.c.21. The ability of the NiTi compression spring to memorize the second way can be seen in figure 3.c.22.

Possibilities for cooling

Cooling by means of flexible tubes

For this experiment one flexible tube was fixed on the shape memory specimen. Figure 3.c.23a shows a cross sectional view of arrangement for cooling by two flexible tubes through which a cooling liquid is pumped. Flexible tubes are charged with water. On this manner it is possible to cool the shape memory specimen. It is also possible to heat them, because both tubes can be charged either by cool or by hot water. This method was successful.

For a better heat transmission we glued a flexible half circle profile tube on the shape memory specimen. Figure 3.c.23b shows a cross sectional view of arrangement for cooling by one flexible profile tube. This profile tube was also charged by cool and hot water. This method of cooling and heating was more effective than the first method mentioned above.

Cooling by Peltier elements

Peltier elements in combination of Seebeck and Peltier effect produce in dependance of polarity cooling or heating at the junctions of the thermocouples of two conductors or semiconductors on condition of current passage. These thermoelectrical components are used as cooling elements e.g. in other electronic components or small refrigerators. Construction of a Peltier element is shown in figure 3.c.23c.

Peltier elements

Single-stage Peltier elements (figure 3.c.23d, 3.c.23e) can obtain a maximal Δ T between both ceramic surfaces of about 65 K. This Δ T is partitioned equally over the ambient temperature. Life-span amounts to usually 100,000 hours, if working and storage temperatures amounts to maximum 80 ° C . If temperatures are higher cooling elements strain faster because copper molecules diffuse into the semiconductor material. Besides, there arises the possibility, that the soldered joint between copper and ceramics smelts. Melting point of tin-bismuth-solder is lower than 136 ° C.

It is very important to keep the Peltier elements dry because they can corrode very fast in case of moisture. For the amelioration of thermal contact between the object to be cooled and the cooling element it is advantagous to use a layer of thermal conduction mass with thickness less than 0.025 mm. Accordingly, the surface roughness of the element to be cooled should amount to 0.7 - 1.7 µm which is adequate to fine emery.

Peltier elements can be soldered at their ceramic surfaces. But because thermoelectric voltages arise, it is useful to do that only for ceramic surfaces with dimensions up to 15 mm x 15 mm. Producer recommends to use a solder of indium (52 %) and tin (48 %).

Experiments fol cooling with Peltier elements

Theoretically, Peltier elements are only conditionally suitable for cooling of CuZnAl-bending elements, because heating of the Peltier element to a temperature higher than 80 ° C should be avoided. But the Af temperature of our shape memory alloy amounts to 80 ° C. For a "commercial" cooling with Peltier elements should be used such shape memory alloys with transformation temperature minimum 5 K lower. Using this thermoelectrical elements such a bending element could be not only cooled, but also heated in case of pole reversal of electrical connections.

For following experiments Peltier elements with dimensions 8x8x4 were applied. If they are put on the bending element, it is less practical, because they do not sit closely on the bending element, but have contact only in one point.

For making this method more effective, Peltier elements were cut between n- and p- conductors with a diamond charged cutting-off wheel in small strips. These strips were glued side by side on the CuZnAl-bending element and connected one with each other electrically (see figure 3.c.23f). On this manner, the bending element can be heated and cooled on an accelerated way.

The most effective cooling methode would be possible with flexible Peltier elements. But producers or suppliers do not deliver such elements. Therefore we tried to produce such a flexible cooling elements ourselves. We decomposed Peltier elements and sorted its pieces accordingly to n- and p-conductors. The copper bridges were replaced by flexible copperplates, on which the n- and p-conductors were solded by bismuth-tin (see figure 3.c.23f).

The ceramic plates were eliminated completely. For practical use it is necessary to isolate cooling element electrically from bending element. The lower flexible cooperplates can be replaced also by a structured coppercoated printed card. First experiments showed that this flexible Peltier element functions like a conventional Peltier element and therefore it should show the best cooling.

<u>Comparison of cooling variants</u>

Cooling by flexible tubes which are filled with a cooling fluid is very effective, but a big number of feeding and discharging tubes plus pump are necessary. Besides, this variant demands additional valves and a control system in order to move each memory part of a whole system of suchlikes.
Many complex components would be necessary for a movement of a relative simple system of shape memory alloys.

In contrast to it cooling with Peltier elements cut in strips (flexible Peltier elements) seems to be a very good solution. Shape memory elements can be cooled and heated very simply. Only a supply point and an electronical control system are necessary for this variant. But this solution is not as good as it seems to be at first sight. The experiments show that it is not easy to keep a big value of ΔT over a long time between the warm and the cold side of the Peltier element. In order to have the possibility for permanent cooling, it is necessary to take away the heat from the warm side. Glued cooling ribs caused a considerable amelioration of that cooling.

Up to now, further possibilities for a fast and effective cooling of shape memory alloys have not been found. It is necessary to make further experiments on this area.

Training of sme elements

The shape memory effect is not given to the springs per se. Therefore a training mechanism was evaluated to give desired shape memory. We will discuss this subject in more detail in the next report but will show here first results of our tests. Basically the training has to be done under certain temperature-deformation conditions where the temperature is changed from one deformation to the other. Figure 3.c.16 to 3.c.20 show sme elements after different training conditions.

These results are combined to show in figure 3.c.21. Figure 3.c.22 underlines the effect of training. Shown is the ability of a sme to memorize the shape after different temperature-deformation circles.

Two-Finger-Tweezer

Figure 3.c.24 shows the construction of each finger. Each finger comprises 4 segments, each having 3 sme. These sme will be heated by indirect electric current. The electric current will pass electric conducting rubber which will heat up under those conditions. Because of the good uninterrupted interface between sme and rubber heat will flow into the sme to heat up sme. Each sme can be connected individually by driver electronics. MOSFET drivers are shown schematically in figure 3.c.25 of the report. The amount of current is controlled by puls-wide-function in current, figure 3.c.26. We constructed an electronical board to interface the tweezer to an IBM compatible computer, figure 3.c.27.

The tweezer can be controlled by pressing certain keys at the keyboard of the controlling computer. One the upper left side of the first sequence of the video one can see the tweezer finger as indicated on the computer screen. The operator will move the points 1 - 4 of the finger individually by the keyboard to control the finger unit. The program itself will decide which element of the 12 to heat in order to move the finger in the desired way.

It seems obvious that the tweezer moves very slow. We have not added cooling devices such as described in paragraph B to this device.

Long sme wire to act as an muscle

In figure 3.c.28 you can see a setup of the experiment shown in the second sequence of the video.

Shown is a tube 1 which is conected via pivoaxis 8 to a wheel 2 which itself is closely conected to a second tube 3. Second tube acts as an arm to hold the weight 4 of 400 g.

A shape memory wire 5 is connected from point 7 inside the tube 1 via hole 9 around wheel 2 to point 6. Not shown here is the electrical connection which can be directly inserted through the sme wire 5. If the wire is heated, it will contract and lft the weight 4. This is shown in the first sequence of the video which is attached to this report.

Small Robot Hand

Such an sme wire 5 will therefore act as an muscle. The weight 4 will always pull back the wire when not heated anymore to lenghten it. Instead of the weight, a second sme wire could pull back the first one. This has proved to be a good principle of moving fingers of small robot hands.

In figures 3.c.29 to 3.c.33 is shown the construction of the robot hand as shown in the video. All measurements are in millimeters. It is a mechanical hand, 11 mm in diameter to pass through a medical trocar, with 3 fingers each comprising two phalanxes. Each phalanx is connected to two sme wires which work against each other in the sense explained above. These sme wires are located in the tube (shaft) holding the robot hand. The video shows just one phalanx of one finger moving. We can only show this one phalanx because we just got to this point. But it now seems easy to add more sme wires to the hand unit to complete it. This is underlined by the fact that we already completed the hand itself. Just the driving motor sme-wire has to be added.

The robot hand got a glove around it for the reason to protect the mechanic of the device from blood coagulation.

Shape-Memory-Conclusion

A small 3 finger robot hand could be demonstrated with yet only one phalanx to move. It was shown how basic experiments where done in order to evaluate the shape memory elements to act as the driving motor for the hand device. It is only a matter ot time until the second report to demonstrate the whole hand. Shape memory elements for driving the robot hand can be used, but are generally too slow and therefore had to be replaced by the bowden pulley construction as described in chapter 3.a and 3.b of this report. With the knowledge of the chapter 3.a to 3.c. an improved distal hand was tested.

3.d Improvement of Distal Hand

It it very important that the hand works in a proper way doing surgical operation. Therefore we did different mechanical tests to stress the mechanics of the robot hand.

Measurements of the Destructive Forces on the Distal Hand

The force-sensing device is fastened to a test platform also serving as guidance for the linear slide. Fixing devices are mounted on both force-sensing device and linear slide in order to fix fingertips and cores. The experimental setup 2 is shown in figure 3.d.1. At first, the test is carried out with comparison fingertips, i.e. no originial parts are used, but geometrically similar parts called comparison fingertips. The geometry of a finger tip is highly complex. In case of the comparison fingertips, one does, e.g., without the bevelling and ribbings which have nothing to do with the fixing of the core. Only place, size, and length of the drill hole are important, and these parameters are taken. We did without the other phalanxes which perform the surface pressure on the core sides. They will, however, be added in further test. The tie force is realized by rotation of a screw screwing itself into fixing elements. This rotation is done by a battery-powered drill.

Core pieces of 20 mm length are used, which are bent by 90° as shown in figure 3.d.2. The core pieces are fixed on the force-sensing device and put into the drill holes of the comparison fingertips. The comparison fingertips are fixed on the linear slide.

Evaluation of the Test

While testing, we observed that the parameters did not change during the test. The maximum values measured are shown in list 2. In general, it could be observed that the forces measured are not sufficient to apply the forces needed (50N) onto the fingertip.

List 3D1

Measured Values during test 2

List 3D1	$\varnothing_B = .5$ mm F in N	Diameter $x_{d,F}$ in N
Variant 1	19.7 34.8 39.2 32.4 35.6	32.34

Possibilities for Optimization of the Core Fixing

There are different possibilities to optimize the core fixing on the distal fingers. That could be a change of the lever geometry, i.e. a change of the distance between the drill holes, or a modification of the fixing possibilities (different bendings of the core, variable diameters of the drill holes).

In addition to that, one could test something completely new by applying other methods of operation, as, e.g., torsional spindles or something similar. One could also try using less elastic materials.

Since any improvement should concern a modification of the core fixing and thus the finger geometry should stay unchanged, any solution was to be limited to variable drill hole diameters, bending possibilities of the core, and, possibly, thermal connection technolgies. The variants of the bending possibilities are described below as shown in figure 3.d.3 to 3.d.5. The drill hole diameters vary in each variant between 0.5 mm, 0.45 mm, and 0.4 mm.

Variant 1: The core was bent once by 100°, thus providing a prestress when mounting (in the drill hole adjusted to 90°). The principle is shown in figure 3.d.2

Variant 2: The core was bent twice by 90°.

Variant 3: The core was bent three times by 90° as well as soldered punctually.

Variant 4: The core was bent four times. The sides lying parallelly were soldered with an I - seam.

Force Measurements on the Optimization Variants

Test Performance

For realizing the different variants, core pieces of 20 mm length are prepared (bent in detail and soldered if necessary). The drill hole diameters in the prepared comparison fingertips vary between 0.4, 0.45, and 0.5 mm. The performance of the test is the same as with the mesurements of the destructive force on the distal hand. We proceeded variant after variant, beginning with the biggest diameter followed by the smaller diameters.

With the first variant, the 0.5 mm diameter could be left out, since those measurements had already been carried out in the first test. At first, tendentious measurements are carried out, i.e. all variants are tested. In case of the optimum values, at least 5 measurements are performed in order to increase certainty.

Test Evaluation

Several dependences could be observed during the test.

1. The allowance between drill hole and core should be as small as possible, i.e. the 0.45 mm diameter is to be preferred. The 0.4 mm diameter cannot be used as the core is not arrranged rotatably any more. The 0.5 mm diameter could be an alternative in case of a bigger core diameter.

2. The number of bendings. Variant 2 is to be preferred here, as the solderings require a lot of work on assembly. Besides this, the adjacent walls in the whole finger have not been considered in the test (Further test are still to be performed).
3. In case of the solderings of variant 4, it is to be observed that the core is freed from its Teflon layer, as well as, upon bending, the core sides lie parallelly in a vertical level to each other, and that the length between the second and the third bending is as small as possible. Both these parameters are essential for the quality of the soldering and thus for the force. The values measured are shown in lists 3.D.2 to 3.D.5.

List 3.D.2 - Improvement variant 1

	$\varnothing_B$ = 0.45 mm, F in N	$\varnothing_B$ = 0.4 mm, F in N
Variant 1	55.7	160.7
	39.1	
	42.1	
	46.3	
	40.2	
Average force $x_{d,F}$	44.68	160.7

List 3.D.3 - Improvement variant 2

	$\varnothing_B$ = 0.5 mm, F in N	$\varnothing_B$ = 0.45 mm, F in N	$\varnothing_B$ = 0.4 mm, F in N
Variant 2	36.4	118.8	158.1
	36.8	113.8	
		113.8	
		76.4	
Average force $x_{d,F}$	36.6	105.7	158.1

List 3.D.4 - Improvement variant 3

	$\varnothing_B$ = 0.5 mm, F in N	$\varnothing_B$ = 0.45 mm, F in N
Variant 3	61.8	182.1
	65.6	164.2
		158.1
		156.4
		162.1
		161.7
		167.0
		132.0
		139.9
		142.7
Average force $x_{d,F}$	63.7	156.62

List 3.D.5 - Improvement variant 4

	$\varnothing_B$ = 0.45 mm, F in N Teflon burned off	$\varnothing_B$ = 0.45 mm, F in N Teflon grinded off
Variant 1	105.1	186.7
	118.6	199.8
	188.0	199.7
	171.1	248.4
	140.2	221.8
	192.5	247.5
	195.8	217.5
	139.1	160.6
	145.7	198.0
Average force $x_{d,F}$	155.12	208.88

Further Possibilities of Optimization

As mentioned before, there are tests to follow concerning the conditions on the distal finger. In detail, fingers comprising two phalanxes will be manufactured.

The importance of the second phalanx is the following:

1. It guarantees the core ends fitting closely to the walls.
2. Two further variants for inclusion of the second bending can be tested.

Another test is to be seen as a test for other materials, i.e. optimization tests by using harder materials.

Force Measurements with a Complete Distal Finger

Test Performance

Prior to the test performance we discussed the question of how to integrate a double-bent core into the fingers. We recognized that several possibilities could be applied, fig. 3.d.6 and 3.d.7. One could provide the guide web of the fingertip (1a) with two cuts (3a), thus shortening the length of the drill hole. Also, a usual fingertip can be used (1b), and be provided with cut (3b) into the bifurcation of the middle phalanx. It is also possible to avoid the double bending by bending the core once and putting a disk onto the second cut on the fingertip, and then soldering this with the bent core. This solution has not been accepted, however, as it would require too much work upon assembling and possible proud soldering drops or core points could gall onto the fork.

Both these variants are shown in figure 3.d.6 and 3.d.7. The rest of the test stays unchanged. The core pieces are put into the drill hole and bent, the fingers are assembled, then the core end and the finger are tensed on the test platform und stretched with a battery-powered drill.

Test Evaluation

After the first two stretch tests, no increase of the tie force was to be observed on the first variant (2 cuts) in comparison with the first tests without additional side. On the second variant, however, a force increase by approx. 40 N was to be observed due to the width of the web left after the cut. The test fingers could not be used any more after both pullings due to the widening of the drill hole on the upper edge. The tendency could be recognized, though, which was enough for the moment. The measuring values are shown in list 3.D.6 and 3.D.7.

List 3.D.6 - Measuring values on the symmetric test body

Symmetric test body	$\varnothing_B$ = 0.45 mm, F in N
Material: 1.4301	116.0
1.4542 (calcined/ hardened)	117.5

List 3.D.7 - Measuring values on the asymmetric test body

Asymmetric test body	$\varnothing_B$ = 0.45 mm, F in N
Material: 1.4301	160.0
1.4542 (calcined/ hardened)	---

<u>Application Test with Other Materials</u>

Test Performance

In the 5th test, the test bodies are made of rust-free high-grade steel which can be hardened by precipitation hardening (17Cr-4Ni) in order to test whether similar widenings on the edge of the drill hole are also to be observed in case of a precipitation-hardened material. The solution-annealed material is calcined one hour at 482°C (± 9 °C) until reaching maximum hardness and firmness and then cooled down to room temperature in the air.

If these conditions are considered upon thermal treatment, the material is made according to condition H900 (statement of manufacturer, internal name/ manufacturer) with the following mechanical firmness data:

Stretching limit	=	1,262 Mpa
Tensile strength	=	1,365 Mpa
Stretching	=	15%
Stretch at break	=	52%
Hardness	=	44 HRC
Notched bar impact work	=	21 J
Modulus of elasticity	=	$1.97 \cdot 10^5$ Mpa

[Precipitation-hardened high-grade steel, G. Früchtl High-Grade Steel Wholesaler, Esslingen, Germany, 1997)

All other parameters such as variants of the cut, experimental set-up, and test performance stay the same as in the previous test.

Test Evaluation

In case of this experimental run, the same problem occured after the first stretching tests. That means, the same forces were measured and the same widenings were to be observed. That led to the following questions:

1. Was the right material used?
2. Was the material delivered with the right conditions (after solution annealing)?
3. Were the ageing parameters observed?

To solve these questions, a hardness grading was carried out on the usual material as well as on the newly used material untreated and aged. No differences in hardness could be observed in case of the specimens hardened by Labor für Umweltanalytik, Schwerin, Germany (Laboratory for environmental analytics) as well as the usual material, thus questioning the process of hardening. Therefore, a new calcining process was performed under supervision of qualified personnel at the college at Wismar, Germany. Upon hardness grading of these specimen, the parameters aimed at and stated in the manufacturer's catalog could be achieved as shown in list 3D8.

On the basis of this knowledge, we decided to use the new material 17 Cr-4Ni (the annealing process could possibly be left out, since there is not much difference in quantity to the unannealed state), and to change the drill hole or rather the remaining wall thickness of the drill hole (core fixing) constructively. To show the final evidence, another testing body was built and and tested in a last test for the time being.

List 3.D.8 - Hardness test

	Hardness Rockwell C
Specimen 1 17Cr-4Ni untreated	40.8 42.8 41.8
Specimen 2 17Cr-4Ni hardened	45.0 44.3 44.3
Specimen 3 18Cr-Ni10 usual	26.0 26.2 725.9

Combination of Previous Variants

One final test was performed using all parameters known and thought to be recommendable. This concerns the bending of the core as well as the manufacturing of the fingertips and the material used.

Testing Method

The testing body was made of high-grade steel able for precipitation hardening (17Cr-4Ni) was already hardened (tests at the college). The second variant with the asymmetric testing body with one cut and a drill hole moved back by 2/10 as shown in figure 3.d.7 was preferred, since, as already stated before, it was to be observed that the remaining wall thickness of the drill hole (or the length of the drill hole) becomes too small and thus the effective bearing area also becomes too small.

Test Evaluation

Four stretching tests have been performed, three with a double-bent core and one with a single-bent core. The latter was performed for demonstrating once more that it is not sufficient to reduce the diameter and to use a harder material. The stretching tests with the double-bent core showed the effects desired. The drill hole remained obviously unchanged (widening only after the last test), and the core did not slip out of the drill hole any more but tore on the edge of the first bending. The measuring values are stated in list 3.D.9.

List 3.D.9- Measuring values of the final force measurement

	$\varnothing_B$ = 0.45 mm, F in N	Average force $x_{d,F}$
Single-bent core	49.9	49.9
Double-bent core	130.2 179.3 169.1	159.53

Construction of a spreading movement on the Robot Hand

A spreading movement of the fingers of the manipulator shall improve the handling and increase the number of application possibilities. The general problem is the lack of space given by the trocar tube (inner diameter = 10 mm) which affects, above all, the guiding of the actuating wire drawings. Since any increase in the movability of the manipulator (spreading movement) inevitably causes an increase in the number of actuating wire drawings, these actuating wire drawings must be smaller in diameter or completely new movement processes are to be developed.

Requirements on a spreading manipulator

The manipulator must meet the following requirements:

1. 45° spreading movement between two fingers
2. 90° swivelling of the thumb
3. 50 N closing pressure on the fingertips
4. 8 N spreading and swivelling power
5. Actuating wire drawings: usual core, nickel-titanium cover
6. Possible torsion transmission

Possibilities of Realization

There are two possibilities of realizing the spreading movement:

Variant 1: Spreading by shifting

Variant 2: Spreading by rotation

A spreading by shifting is possible by spreading the fingertip angularly, for example by

- mounting a claw onto the basic finger joint
- construction of a cardan or ball-and-socket joint

A spreading by rotation can be realized by rotating one finger transversaly to the grip movement (opening and closing).

Spreading by Construction of a Claw

The basis for the construction of the first version of the spreading manipulator was a trainee's project of the year 1994. The basic idea was to move the fingers by means of springs, i.e. the fingers closed by pulling an actuating wire drawing against a spring and opened by releasing the spring. Spring and actuating wire drawing formed a unit by the spring being the cover of the core of the actuating wire drawing. Therefore it was possible to leave the cover out by guiding the actuating wire drawing through the fingers (the drill hole in case of a guidance with cover would be too big, the remaining wall thickness too small). Since it is not possible to position the finger at any place one likes without an explicit grip of the operator, however, this possibility has never been built. But the results of this practicum project allowed the choice of smaller diameters for the actuating wire drawings.

It was therefore tried to build in additional joints (such as a claw for the pointer or a swivel tip for the thumb), and to guide the actuating wire drawings through these joints without influencing the finger movements (opening and closing). The sketches for this solution variant are shown in figure 3.d.8 and 3.d.9.

The decrease in diameter of the actuating wire drawings was not sufficient to mount an additional joint. The joint would be likely to be unstable owing to the different guidance drill holes for the actuating wire drawings. Besides that, it is to be feared that an influence on the various movements cannot be excluded, since a pressure is load onto the movements by the different angles of the guidance drill holes. It was therefore decided not to consider this variant any more for the time being.

Rotating Fingers

The basic idea for this second variant was the wish to grasp a cylindrical object laterally to its base and in the center, as well as to allow the forwarding of tubes, blood vessels, or threads bit by bit. The idea for realization was closely connected with a project where the usual transmission distance with actuating wire drawings should be replaced by a transmission distance with torsion spindles, i.e., it should be possible to rotate the finger on a circuit laterally to the finger movement as shown in figure 3.d.10.

Sketch of Rotating Fingers

Upon construction, we tried to connect the existing movement processes. We used two usual fingers by modifying the geometry and dividing the middle part of the finger into two parts, fig. 3.d.11. The first half was bent to the middle of the finger, and the second half to the finger bend 2. A swivelling shell was soldered into the middle of the finger and arranged rotatably in the finger bend, fig. 3.d.11. The rotation of the finger shall be realized by rotation of the nickel-titanium cover, i.e., the nickel-titanium cover must be guided through the swivelling shell and fixed therein, i.e. the swivelling shell is, as the name indicates, hollow, as can be seen in figure 3.d.11.

Improvements of the Torsion Proofness of the Nickel-Titanium Cover

The strong torsion is not easy to handle, especially since the nickel-titanium cover must remain movable in the direction of the tension, as, owing to the grip movement of the finger, there is a change in length. Thus, a twisting of the nickel-titanium cover is not possible in the usual way. Possible would be a spring twisting, which would be likely, however, to lead to a jerkily rotation of the finger. We therefore had to think about how to avoid this torsion. The nickel titanium cover was prepared in the same way of technology as described in chapter 3.c.

With the results of the force measurements, the turning moment necessary for the calculation of the torsion potential can be determined for choosing a material with a greater torsion proofness.

Moment Calculation

An average force of 2.02 N has been calculated on the basis of the five measurements. For the moment calculation according to equation (1), the force is rounded up to 3 N owing to safety reasons.

Equation (1): $M_t = F \times R$

$M_t = 3\ N \times 4\ mm$

$M_t = 12\ Nmm$

Calculation of Torsion Potential

The torsion potential can be calculated according to equation (2):

$T_t = M_t / W_t$

Before this, the section modulus W_t of a perforated diameter must be calculated (3):

Equation (3): $W_t = \pi / 16 \times (D^4 - d^4) / D$

$W_t = \pi / 16 \times (1.2^4\ mm^4 - 0.8^4\ mm^4) / 1.2\ mm$

$W_t = 0.272\ mm^3$

$T_t = 12\ Nmm / 0.272\ mm^3$

$T_t = 44.117\ N/mm^2$

Choice of a Material for the Covering Cannula

At first, we saught materials which are already availble in the company as cannula tubes (Acufirm Needle Factory E. Kratz, Dreieich, Germany). Only those cannulas could be applied for the dummy production which have a suitable internal and external diameter (0.8 mm/ 1.2 mm). The cannulas are made of rustless, austenitic chrome-nickel steel which is resistant to desinfection (high chemical charge). Two materials are possible:

X5CrNi1810 with R_m = 500-700 and R_{p02} = 195 N/ mm²

X5CrNiMo17122 with R_m = 510-710 and R_{p02} = 205 N/ mm²

The first variant has been chosen, since the safety factor for the stretch limit R_{p02} has a minimum value of 4.

$T_t = 44.117\ N/mm^2 \leq ½ * 195\ N/mm^2$

Fixing Possibilities of the Cannula

The following fixing possibilities can be applied:

- Soldering with tin-lead solder or brazing filler metal
- Glueing
- Laser welding

Soldering

The main problem in case of soldering of titanic alloys is the moistening of the surface. In the concrete case, the soldering of nickel-titanium cover, this means that the share of titanium within the alloy is too high to achieve an unproblematic moistening of the solder. We therefore investigated in the field of fluxing agents and discovered the company Wieland High-Grade Metals, Soldering and Fluxing Agents of Pforzheim which provides several fluxing agents for this problem. These are fluxing agents with the inernal name FU40 and Certoflux with the brazing filler metal AgL60 and AgL72. The latter already shows the disadvantage: In case of brazing, the nickel-titanium cover is glown away, looses any elasticity, and breaks at the point of bending.

Upon testing, not only a connection of the nickel-titanium cover with the stiffening cannula was observed, but also the soldering of the fingers. For the soldering tests on the fingers we used the comparison fingertips already known and provided them with soldering splits. Upon brazing, it was to be recognized that AgL60 with Certoflux is the best combination possible. The fluxing agent moistens the stainless steel surface completely, so that the complete soldering split was filled with solder. The silver filler AgL72 was more difficult to handle, since the heat within the comparison fingertip was dissipated via the fixing too fast for keeping the solder liquid steadily. In case of the fluxing agent FU40, the heat seemed to be too high. It vaporized immediately upon filling and the solder dripped off.

For soldering tests with the cannula, we used the knowledge of previous tests. Knowing that the nickel-titanium cover glows away upon brazing, we tried to combine the usual soft soldering process with the new fluxing agent, since especially the end exposed from the cannula should have the elasticity desired in case of the nickel-titanium cover. Upon soldering of the stainless steel (Soldamoll 220 solder and Soldaflux Z fluxing agent) with the nickel-titanium cover (FU40 fluxing agent) we also achieved useable results. The moistening was good, and the consistency was comparable (since the strain was very low, a stretch test with tongs was performed).

Glueing

Three glueing tests with three different bonding agents have been performed (Anerobe bondig agent of Locite Deutschland GmbH of Munich). These were two mixed adhesives (Epotec, Loctite 3430), and one shaft seal bonding agent (Loctite 601). The test results are shown in the following list.

	EPOTEC	LOCTITE 601	LOCTITE 3430
Components	2	1	2
Consistency	moderately fluid	mobile	consistent
Spontaneous Increase in Hardness after/ by	3 - 4 h heat and reaction of the components	3 - 4 h heat	30 min reaction of the components
Consistency after Heat Influence	becomes brittle	becomes brittle	no restrictions
Size of Adherend	bonding agent fills the glueing split well, resulting in the best adherend possible	bonding agent fills the glueing split by far best, but results in a bad adherend due to the lack of anerobe characteristics	bonding agent does not fill the glueing split well, but moistens the surface well, thus resulting in a good adherend
EVALUATION	not suitable	not suitable	well suitable (no request concerning medical suitability so far)

Laser Welding

The nickel-titanium cover with its wall thickness of 0.075 mm is not suitable for laser welding. The cover would melt, not allowing the guidance of a core any more. In addition to that, a microstructural change were to be observed, concerning only a small region, but possibly leading to a rupture in case of bending strain. The results of the laser welding tests showed, however, that laser welding allows an optimization of the fixing of the swivelling shell guiding the rotation movement of the finger.

Results of the Investigations

By using a covering cannula, the elasticity of the nickel-titanium cover was limited for transmitting a rotation. A bending outside the cannula is nevertheless possible. The cannula is glued together with the nicke-titanium cover (LOCTITE 3430). Different ways of fixing the nickel-titanium cover are possible upon assembling of the fingers:

1. The swivelling shell is soft-soldered with the middle of the finger, then the nickel-titanium cover is also to be soft-soldered (with FU40).
2. The swivelling shell is connected with the middle of the finger by laser welding; brazing is also possible.
3. Glueing in place would also be possible in both cases.

Referring to the figures, wherein like numbers denote like parts throughout the several views, fig. 3.d.12 shows a robot hand 1 generally consistent with the principle of the present invention. The robot hand 1 is constructed to mimic movements of a remote human hand or other mechanical and/or electrical devices such as a computer, as generally shown in fig. 3.d.16.

In fig. 3.d.12 the robot hand 1, similar to a human hand, has a thumb 2, a first finger 3, a second finger 4, and a hand base 5. The robot hand 1 can be covered by a glove 6 as shown in fig. 3.d.13. As shown in fig. 3.d.12, the thumb 2 includes a base phalanx 7, a middle phalanx 8, and an end phalanx 9. The fingers include a base phalanx 7', 7", a middle phalanx 8', 8", and an end phalanx 9', 9", respectiveley. Each end phalanx 9, 9', 9" is disposed at a distal end 100, 100', 100" of the thumb 2 of fingers 3, 4. Each end phalanx 9, 9', 9" has a proximal end 102, 102', 102". Each middle phalanx 8, 8', 8" has a proximal end 104, 104', 104" and a distal end 106, 106', 106". Each base phalanx 7, 7', 7" has a distal end 108, 108', 108". The proximal end 102, 102', 102"of the end phalanx 9, 9', 9" is pivotably attached or coupled to the distal end 106, 06', 106" of the middle phalanx 8, 8', 8" for rotation around a distal axis 110, 110', 110". The proximal end 104, 104', 104" of the base phalanx 7, 7', 7" is pivotably attached or coupled to the distal end 108, 108', 108" for rotation around a proximal axis 112, 112', 112". The distal axis and the proximal axis are substantially parallel. Each phalanx is connected to the next phalanx by a joint [10]. As shown in fig. 3.d.12, the end phalanx 9, 9', 9" is coupled to the middle phalanx 8, 8', 8" by middle phalanx joint 115, 115', 115", and the middle phalanx 8, 8', 8" is coupled to the base phalanx 7, 7', 7" by proximal phalanx joint 116, 116', 116". The joint 10 can be any type of suitable connectors, such as a coupled hinge, as shown.

Fig. 3.d.13 shows the robot hand 1 covered by glove 6, which is made out of an elastic material, such as silicone, latex or any other suitable kind of rubbr or elastic material. The glove 6 can serve to protect the mechanics of the robot hand 1. The glove 6 also can provide for repeated sterile use of robot hand 1 and reduce the cleaning necessary after use. In addition, glove 6 can make it easier for the gloved robot hand to move along a lumen or other medical guide such as a trocar. The glove further helps prevent pinching of structures along the path that the robot hand passes through.

Furthermore, the glove 6 can be disposable after an operation of the robot hand 1, e.g. an endoscopic surgical procedure. It will be also appreciated that the hand glove 6 can be made corresponding to the modified robot hand, e.g. with additional finges, without departing from the scope and spirit of the present invention.

In fig. 3.d.14.a and 3.d.14.b, a longitudinal cross-sectional view of the first finger 3 is shown. The cross-sectional views of fig. 3.d.14.a. and 3.d.14.b could also be representative of finger 4 or thumb 2. As illustrated, middle phalanx joint 115' connects the end phalanx 9' to the middle phalanx 8' so that the end and middle phalanxes 9' ad 8' are relatively rotatable around the distal axis 110'. Proximal phalanx joint 116' connects the middle phalanx 8' to the base phalanx 7' so that middle and base phalanxes 7' and 8' are relativeley rotatable arond the proximal axis 112'.

Mechanical pulley or cable 13' extends in a bore 50' of the end phalanx 9', a bore 51' of the middle phalanx 8', and a bore 52' of the base phalanx 7'. The distal end of the pulley 13' is connected to the end phalanx 9' at location 14' proximate to the proximal end 102' of the end phalanx 9'. This connection can be done by fastening means such as a screw or other means such as welding, gluing, etc. via a hole 15'. A spring 17' is disposed around a portion of the pulley 13' proximate the middle phalanx joint 115' between the end phalanx 9' and the middle phalanx 8'. The two ends of the spring 17' are retained in notches 124', 126' of the end phalanx 9' and the middle phalanx 8'., respectively. The spring 17', biased against and between the walls of the two notches 124', 126', can be a spiral or a flat spring or their equiavalents. The pulley 13' is operated to move the end phalanx 9' against the middle phalanx 8', which mimic movements of a thumb between the end and middle phalanxes. Accordingly, when the pulley 13' is pulled in a direction of the hand base 5, the end phalanx 9' moves against the middle phalanx 8' around the distal axis 110 as shown in fig. 3.d.14.a. When the force to pulley 13 is released, the spring 17' biases back the end phalanx 9' from the middle phalanx 8' around the distal axis 110' so as to straighten the finger 3 as shown in fig. 3.d.14.b.

Mechanical pulley or cable 12' extends in a bore 120' of the middle phalanx 8 and a bore 122' of the base phalanx 7'. The distal end of the pulley 12' is connected to the middle phalanx 9' at alocation 128' proximate the proximal end 104' of the middle phalanx 8. This connection can be done by fastening means such as a screw or other means such as by means of welding gluing, etc. via a hole 130'.
A spring 132' is disposed around a portion of the pulley 12' proximate the proximal phalanx joint 116' between the middle phalanx 8' and the base phalanx 7'. The two ends of the spring 132' are retained in notches 134', 136' of the middle phalanx 8' and the base phalanx 7', respectively.

The spring 132', biased against and between the walls of the two notches 134', 136', can be a spiral spring or a flat spring or their equivalents. The pulley 12' is operated to move the middle phalanx 8' against the base phalanx 7', which mimic movements of a digit (finger or thumb) between the middle and base phalanxes.

Accordingly, when the pulley 13' is pulled in a direction of the hand base 5', the middle phalanx 8' moves against the base phalanx 7' as shown in fig. 3.d.14.a. When the force to pulley 12' is released, the spring 132' biases back the middle phalanx 8' from the base phalanx 7' so as to straightend the finger 3 as shown in fig. 3.d.14.b.

Finger 4 and thumb 2 have a similar longitudinal cross-sectional view as shown in fig. 3.d.14.a and 3.d.14.b. As a result, the two pulleys of (12, 13, and 12' and 13") each of the fingers 3 and 4 move the middle phalanx 8, 8" against the base phalanx 7', 7" and move the end phalanx 9', 9" against the middle phalanx 8', 8".

As shown in fig. 3.d.12, the fingers 3 and 4 are generally disposed to oppose the thumb 2 such that the movement between the thumb 2 and each of the fingers 3 and 4 allow gripping therebetween.

Further in fig. 3.d.12, a spring 18 is connected between the base phalanx 7" of the finger 4 and hand base 5. The spring 18 is used to move back (adduct) finger 4 with respect to the finger 3. Another spring (not shown) is connected between the base phalanx 7' of finger 3 and the hand base 5. The spring is used to move back (adduct) the fingers 3 with respect to finger 4. The spring help force fingers open between each other. It is appreciated that the fingers 3 and 4 can be spread from each other (adduct) by means of a cable (not shown).

Still referring to fig. 3.d.12, the thumb 2 can pivot transversely around an axis through pivotal connector 20 or similar pivot arrangement, by means of a cable (not shown), and a pull-back-spring 19. Pivotal connector 20 can be a screw 21. Pivotal connector 20 allows the thumb 2 to move transversely. As a result, the thumb 2 can move against the individual fingers, finger-by finger, so as to grip between the thumb and different fingers. It also allows the thumb 2 to rotate with respect to the fingers in a directions determined by the joints, pivotal connnector 20 and the pull-back-spring 19. Accordingly, the robot hand with the thumb and fingers can mimic the movements of a hand with an opposable thumb, e.g. a human hand.

Referring to fig. 3.d.15.a and fig. 3.d.15.b, a second embodiment of a robot hand 1 is shown. Fig. 3.d.15.b is a tip view of robot hand 1. Fig. 3.d.15.a is a side view of robot hand 1. The robot hand 1 comprises a hand piece 21 with a thumb 22, a first finger 23, and a second finger 24. The robot hand 1 can rotate via pulleys around a pivot point 25 but may not be able to spread (abduct) fingers 23 and 24. In fig. 3.d.15.a and 3.d.15.b, the robot hand 1 includes a wrist 61. The thumb 22 has two phalanxes 26 and 27 which are connected at joint 60. the joint [[10]] 115, 115', 115" or 116, 116', 116" as described for fig. 3.d.15.a can be used between phalanx 26 and 27. In fig. 3.d.15.a, phalanx 26 is extended relative to hand 1 and phalanx 27 is flexed relative to phalanx 26.

It will be appreciated that when the fingers/thumb are generally in their straight positions, the robot hand 1 with shaft 28 attached to the hand is able to pass through a medical guide such as a trocar.

Referring to fig. 3.d.14a and 3.d.14.b, the operation of finger 3 is demonstrated. It will be appreciated that the discussion related to operation and function of finger 3 is applicable to thumb 2, finger 4 and any additional fingers which may be used. The pulleys 12' and 13' can be pulled either by a remote controller or a local controller. As discussed above, the pulley 13' is shown to be located in the finger to cross around proximal phalanx joint 116' between the base phalanx 7' and the middle phalanx 8', moves inside the middle phalanx 8' down to the bottom (volar) side of the finger 3 into the spring 17', and is connected to the end phalanx 9' in the hole 15' at 14'. If the pulley 13' is pulled, the pulley 13' bends the end phalanx 9' against the middle phalanx 8'. If the pulley 13' is loosened, the spring 17' biases against the end phalanx 9' which would tend to straighten the finger between the end phalanx 9' and the middle phalanx 8'. The pulley 13' does not move the middle and proximal phalanx joints 115', 116' because the pulley 13' does not have a spring around it and will cross the joints 115', 116' at the pivot point or dial axis 110'. Fig. 3.d.14.b shows the finger 3 in a straight position where the spring 17' straightens the finger.

A second mechansim of the robot hand is shown in fig. 3.d.15.a and 3.d.15.b. Here the thumb 22 moves against fingers 23 and 24 but cannot move together (i.e. adduction). Also, fingers 23 and 24 cannot move together (i.e. adduction). Also, fingers 23 and 24 connot spread (i.e. abduction).

Fig. 3.d.16 shows that the shaft 28 can be disconnected from a flexible transfer unit 47 by a disconnecting unit 26 so that an exemplary robot hand 29 can be disconnected from the system to be sterilized or disposed and/or changed with a new hand. The cables are retained inside a flexible transfer unit 47 and connected to a motor unit 48. Motors of motor unit 48 can be controlled by a computer 49.

Fig. 3.d.17 shows a cross-section of flexible transfer unit 47 including a pulley or cable with a core assembly 50 and a sheat 51. Fig. 3.f.7 shows the cross-section of another type of flexible transfer unit 47 including a pulley or cable with a core assembly 50, a sheath 51, and a filling 52.

Fig. 3.d.19 illustrates a schematic view of a circuit of a control system. In one embodiment, all control functions are operated and controlled by a micro controller system 42. The robot hand can be controlled by a digital input device 39 or an analog input device 38. The analog input device 38 presets nominal values for the movement of the robot hand.

Program and data for a controller 43 are saved in a working memory. An A/D converter 44 together with an analog multiplexer 40 is used for acquisition of measured values for positioning a robot hand. The serial interfaces RS232 (45) are used to control the robot hand from a master system and to connect the digital input device 39.

The controller 43 produces directional signals which are transmitted by a port multiplexer 41 to a motor controller 31 to control motors 35. The motor controller 31 generates special signals for the motors 35 with interfaces 32 and powers to signals with drivers 34. The motors 35 cna be linerar motors or rotary motors. It will be appreciated that other types of suitable motors can be used.

In one embodiment, the analog multiplexer 40 transmits the signal of position sensors 36 in the robot hand to a channel of the A/D converter 44. A power supply 30 delivers power with a suitable voltage for the motors 35 and for the micro-controller system 42 and port extensions.

3.e Final Robot Hand

Figure 3.e.1
shows the complete assembling of the robot hand.

Figure 3.e.2
shows the distal hand (comparable with the distal hand of chapter 3a)

Figure 3.e.3 and 3.e.4
The distal finger of figure 3.e.3 is arranged rotatingly in the proximal finger of figure 3.e.4. Within the wrist, three fingers are arranged in a way that they allow grasping.

Figure 3.e.5

Joint 1 is the movable part of the wrist, performing the actual swivelling movement. A wire cable is soldered within this joint, transferring the force necessary for this movement.

Figure 3.e.6

The disc serves as a guidance of the wire cable.

Figure 3.e.7

Joint 2 is the fix part of the wrist. Within this joint, joint 1 is arranged, and the whole wrist is connected with the tube shown in figure 3.e.8.

Figure 3.e.9

Assembling wrist

Figure 3.e.10

The guide system 3.e.10 has been reworked by arranging the guide rods shown in figure 3.e.11 on both sides. They are arranged within the flang shown in figure 3.e.12 as well as in the wrist plate of figure 3.e.13, thus preventing a twisting and swivelling of the system and improving the precision and smoothness of running.

Figure 3.e.14. and figure 3.e.15.

The tension blocks are shifted on the rods in slidebushings shown in figure 3.e.16. The wire cable serving for the movements of the joint is fixed tightly within the tension block of figure 3.e.14. Within the tension block 2 of figure 3.e.15., the wire cable is fixed adjustably by means of a bolt (see figure 3.e.17.) and a bolt nut (see figure 3.e.18), thus allowing a tensing and resettting of the wrist without removing the wire cable. We retained the threaded spindle of figure 3.e.19. with two different thread types. Tension block1 is screwed on the M6 x 0.5 left hand, tension block 2 is screwed on the M5 x 0.5 right hand, thus achieving a constant movement of the wrist. For recognizing the position of the wrist, a slide pot is cramped into the tension block by means of two plates as shown in figure 3.e.20.

Figure 3.e.21.

The construction of the gear part has been changed in the following points. The main functions have been retained as described in chapter 3b. The ventilating system has been changed for better cooling and thus longer application by providing the thread of figure 3.e.22. with ventilation drill holes.

The motors are now directly flown against and thus better cooled. In addition to that, we modified the ventilation type, now using turbine ventilations as shown in figure 3.e.23. The boards of figure 3.e.24., serving as seat for the slide pot, have been firmly integrated and screwed within the threads, thus better protecting the position recognition system against concussions.

3.f Finger Spreading

For increasing the movability of the robot hand, facilitating the grasping of round objects, and allowing a well-aimed grasp with the fingertips, the distal hand has been additionally provided with a spreading movement of the fingers. By using a special torsion-proof cover for the compression-tension Bowden cable, the integration of an additional movement without additional transition components and by retaining the existing degrees of freedom, forces, and size was possible.
The finger spreading of the distal hand is explained in the following figures:

<u>Figure 3.f.1 and 3.f.2</u>

show the modified fingers. The former finger has been divided in the middle. The front and rear connection has not been changed, but an additional joint has been integrated in the middle, allowing a lateral swivelling of the fingertip. The swivelling axis lies outside the finger axis. Therefore, the spreading movement is originated upon rotation the finger around this axis.

<u>Figure 3.f.3</u>

The swivelling axis around which the finger rotates is connected with the front part of the finger and arranged flexibly in the rear part and firmly connected with the torsion-proof cover of the Bowden cable.

<u>Figure 3.f.4</u>

shows the fingertip which has not been changed and retains its full functionality.

<u>Figure 3.f.5</u>

shows once again the complete assembly of the new finger. The special Bowden cable for moving the fingertip is led through the swivelling axis to the joint of the fingertip and connected with the swivelling axis. By initiating a torsion onto the cover of the Bowden cable, the front part of the finger is being rotated and will swivel around the swivelling axis. Upon reversing the cover, the finger will also turn back into its original position. The swivelling way is limited by buffers. The movement of the fingertip is not influenced by the swivelling movement and is performed, as it was before, by a special wire.

4. ELECTRONIC ACHIEVEMENTS

Block diagram, Fig. 4.1

Complete circuit of control system is schematically illustrated in block diagram fig. 4.1. All control functions are operated by controller board with TMPS69C141 of Toshiba. TMP96C1412 is a 16-Bit microcontroller with on-chip- 4-channel-A/D converter with 2 serial interfaces. This A/D converter together with the analog multiplexer is used for acquisition of measured values for positioning robot hand. Analog signals from path sensors in the robot hand are connected one after the other with two of the 4 inputs of A/D converter. First serial interface RS232C is used to load control software. Second serial interface serves for the connection of digital input devices.

Microcontroller produces direction and pulse signals which are transmitted by port extension at the driver control unit to the stepper motors. Port extension is realized by bus drivers with latch function.

Driver of stepper motor generates the control signals for the phase windings of these stepper motors and boost them. Driver control unit of pulse motor has an regulator for constant current on the base of impuls width control system which allows to use the motor resources effectively.

Power supply unit delivers the required voltage of 24 V for the motors and 5 V for microcontroller and port extension.

Port extension, Fig. 4.2

Port extension on page 2/7 shows the interface between microcontroller TMP96C141 and drivers of motors. It extends the ports of the microcontroller in an amount of four 8 bit ports which are used for the production of the signals "DIR", "STEP" and "HSM". One 8 bit port triggers the indication unit which indicats the actual status of program. The first of the 8 decoders IC1 decodes the addresses and shows the ports of the microcontrollers in the range from 808008 H to 80800CH.

Analog multiplexer IC7 transmitts always each analog signal of the path sensor in the robot hand and each analog value of the set point sensor in the control board to one channel of the A/D converter in the microcontroller TMP96C141.

Channel can be chosen by bit 0-2 of port 80800CH. These bits are connected with the inputs of the adresses of IC 7. SML-Bus of evaluation board with X1 realizes the connection to the microcontroller.

Driver control systems for the pulse motors are connected over X6-X13 by the port extension.

Driver control system, Fig. 4.3

The Driver illustrated on page 3/7 can be divided into three parts:

step sequence generator

control stage

output stage.

The driver control system realises the generation of pulses for half cycle and full cycle operation modes and contains a regulation of constant current on the base of impuls width control system. By the means of this driver control system pulse motors up to 40 V/5 A can be operated.

Pulse generator is realized by IC17. This IC transduces the direction signal "DIR" and the pulse signal "STEP" into the signals for the activation of motor phases in half cycle or full cycle mode. Time delay between the activation of opposite motor phases can be regulated with R/C combination R1/C49 . This time delay is necessary for reduction of power dissipation of high-level transistors which take a few microseconds to pass from conducting in non-conducting status in dependance from type. For our types we selected a time delay of 30 µs.

Regulation of constant current is realized by IC18. Voltage drop which is proportional to the current in the according winding of motor is measured by means of R93-R98 and R99-R104 at Pin 9 and Pin 16. This measured voltage drop is compared with reference voltage at Pin 8 and Pin 16 over an intern comparator. In the case if adjusted current value is achieved IC18 is turned off by the according high-level stage. Comparison of value of motor current with reference value is realized by a sample frequency selected over R5/C52. In our circuit a frequency of 38 kHz was selected.

DMOS power transistors Q1-Q8 allow a quite dissipationless circuit in the motor windings because these types of transistors have a very low channel resistance in their conducting status and are controllable without power. Diodes D11 - D18 save the high-level transistors against negative induction voltage of motor windings.

Connection to the board extension is realized over X 19. Motors are connected over X20 to the driver circuit. The driver control system has been built for each stepper motor.

Controller board, Fig. 4.4

Controller board contents U1 the microcontroller TMP96C141. TMP96C141 is a high-speed advanced 16 bit microcontroller developed for controlling medium to large-scale equipment. TMP96C141 is housed in a 8⌀ pin flat package. Programms and data for the microcontroller are memorized in the working memory 64k. Monitor program for loading of controlling software is memorized in EPROM IC8. Microcontroller works with a clock frequency of 14,756 MHz which was selected by reasons of compatibility to RS232C-standard. Connection to port extension is guaranteed by X16. Levels of two serial interfaces are converted by IC 16 to RS232C-levels. COM1 and COM2 permit the connection of the interfaces . Diodes D3-D10 save the input of the 1⌀ bit A/D converter from overvoltage and undervoltage.

Analog Control Panel, Fig. 4.5

Control panel presets the analog nominal values for the movement of the robot hand. Position of the according axis can be preset by potentiometers R43-R50. Desired program is selected by switch SW1. The program selected by switch SW1 is shown on LED D1. Selected program can be started by tactile start switch. By stop control the program is finished.

Path sensor, Fig. 4.6

Modules for path sensor shown in fig. 4.6 produce an analog value which indicates the position of the according axis of robot hand. Positioning control system R52, R53, R 55, R 56...R73, R74 allows to adapt the path sensor in an optimal way to the resolution of the A/D converter.

Stepping motors, fig. 4.7 and Fig. 4.8

Connection of stepping motors in the robot hand are shown in fig. 4.7 Robot hand is connected over X23 with control unit. Motors from M8 to M13 are fans which are used to carry off the heat of the pulse motors, fig. 4.8.

5. DATAGLOVE

Daum Inc. has developed a dataglove "DAUMGLOVE" which makes it possible to detect

- the adduction and abdunction of every single finger joint
- the spreading of the finger
- the rotation of the thumb

The "DAUMGLOVE" is easy and comfortable to wear. One can wear it like a conventional glove over a longer time. "DAUMGLOVE" has a serial interface (RS 232C) which can be used with several computer systems like PC, UNIX-Systems and MAC. It is possible to adapt the software protocol depending on the application used. The best solution is to choose the master slave mode with the "DAUMGLOVE" working as the slave. The sensor system is developed and patent protected by the Daum company. It is stable during a long period of time. Because of its low production cost, a "DAUMGLOVE" glove is easy to produce as a mass product.

To measure the finger movement and to analyse the data, we use a two-part measuring system as shown in figure 5.1. This is divided into the data logger and the transducer bank. The data logger is placed on the back of the hand. It can involve a position tracker, function keys and a control LED. The transducer bank is an external device with a serial interface to the computer system and a power connection.

"DAUMGLOVE" can also be used in computer games. To use the "DAUMGLOVE" e.g. in the field of computer games, it is absolutely necessary to minimize the complex funtionality of the electronic components for measuring and analysing finger data. It is our aim to place the active components of the data logger in an ASIC so that we are able to mount the data logger on the back of the human hand which is an area of about 40 x 80 mm.

These active components are:

- analog switching with analog Muxes
- measuring with operation amplifiers
- analog/ digital converting (12 bit)
- galvanic separation
- address coding for Muxes, A/D converter
- data analysis with micro controller

Passive and active components which must also be included in the data logger are:

- connectors for sensor cable and cable to transducer box
- function keys
- LED signal
- position tracker

Because of the analog and digital structure of the active components, it is necessary to use a mixed-signal ASIC. There are great demands on the ASIC technology (e.g. BiCMOS 0.6 μ), because of the high input voltage (>10 V). A separation of the ASIC into an analog and a digital ASIC is not intended at the moment.

The use of an ASIC leads to a fundamental decrease of production costs. It is not effective to build the measurement electronic out of common elements because of its high space requirements and the high costs of the components. So only with an ASIC it is possible to reach the market of home users. For use in the industry, too, it is necessary to minimize space and costs.

If the minimizing of the system by the mixed-signal ASIC will be successful, the transducer bank will only be an interface to the particular serial protocol. The power for the transducer bank will be provided by a wall plug-in power source.

The present invention of the dataglove is directed to an instrumented fabric that can be formed into articles worn by a user to detect motion of various parts of the user's body While these articles worn by the user may take many different forms and be used to detect the motion of many different parts of the user's body, the description of the invention is directed to an embodiment of that includes a data glove in order to help the reader understand the full scope and applicability of the invention.

The use of a data glove as an example is not intended to limit the scope of the invention, which is set out in the claims.

Fig. 5.1 illustrates a general view of a data glove. The data glove 100 is formed of a flexible material that fits to the human hand 106 like a normal glove. The flexible material may include a rubber layer. The rubber layer includes one or more sensors positioned strategically on the glove to detect various motions of the user's hand and digits, such as flexion of a finger joint. The rubber layer may extend partially or completely throughout the glove 100. The glove is provided with fingers 104 and a cable connection 102 so that data generated by the sensors may be transmitted to a signal analyzer. The glove 100 may also include a fastener 108 for holding the glove firmly in place on the user's hand 106.

The fastener 108 may be of the hook and loop type, commonly known as VELCRO.

Fig. 5.2 illustrates a cross section through a portion of an electrically conductive rubber layer, such as may be used in the glove 100. The conductive rubber layer 204 includes a rubber matrix 200, which may be a conventional electrically insulating rubber, a liquid silicon rubber (formed by a vulcanization at high temperatures), or an RTV silicon rubber (room temperature vulcanized). As an example, Silopren 2530, manufactured by Beyer Corp. may be used for the rubber matrix 200.

Electrically conductive particles 202 are inserted in the rubber matrix 200. These particles 202 may be all be formed from the same material, or from different materials, and may have the same or different sizes. The electrically conductive particles may be, for example, carbon (graphite), titanium or aluminum or other metal particles. Additionally, the particles may be a mixture of, for example, carbon, titanium and graphite. The electrically conductive particles 202 may be surrounded with primers (bonding agents). The electrically conductive particles 202 are mixed into the liquid rubber before it is vulcanized to form the rubber matrix 200. The conductivity of the rubber layer 204 arises from the conductive particles 202.

Rubber formed in this manner manifests an electrical resistivity that is dependent on the strain applied to the rubber matrix 200. This is illustrated in Fig. 5.4, which shows the voltage drop measured across a sample of electrically conductive rubber as a function of strain from zero to 15 mm.

The four curves represent different cycles in which the sample was strained: the voltage drop is plotted for each cycle to show the repeatability of the sensor's voltage drop. The unstretched rubber had a resistance of approximately 5 kΩ between electrodes separated by 2.5 cm.

Fig. 5.3.a illustrates a first embodiment of a sensor used in the glove 100 to detect motion of a digit. The figure illustrates a section through the material of the glove 100, between an outer isolating layer 300 and an inner isolating layer 302. The glove material includes two layers of electrically conductive rubber 304, separated by an isolation foil 306. A metallic foil 308 is provided on one side of the isolation foil 306. A gap 310 formed in the metal foil 308 is filled with another layer of insulation 312. A pair of insulation gaps 314 expose parts of the upper surface of the metallic film 308 to the conductive rubber 304. These exposed portions 320 of the metallic film 308 act as electrodes.

The left portion of the metallic film 316 is electrically isolated from the right portion of the metallic film 318 except for the electrically conducting path from the electrodes 320 through the electrically conductive rubber 304. The metallic foil 308 is connected to a system (not illustrated) for measuring the resistance around an electrical circuit that includes the metallic film 308 and that portion of the electrically conductive rubber 304 lying between the electrodes 320. If the glove material is stretched in a lateral direction 322, for example by flexing of a finger, then the conduction path between the electrodes 320 changes, thus changing the electrical resistance measured. For example, if the length of the conduction path increases, e.g. through stretching the rubber, then the electrical resistance also increases. Conversely, if the length of conduction path is decreased, for example by compression of the rubber, then the resistance falls.

In another embodiment, illustrated in Fig. 5.3.b, the glove material includes outer and inner insulating layers 330 and 332. A layer of electrically conducting rubber 334 is disposed between the outer and inner insulating layers 330 and 332. Helically wound, isolated wires 336, also called electrodes, are disposed within the electrically conductive rubber 334. Each electrode 336 includes a wire surrounded by a layer of insulation 338, and a bared metal tip 340. The electrodes 336 may be connected to an external circuit (labeled as "C", not shown) so that current flows between the pair of bared metal tips 340 through the conducting rubber 304.
The circuit may be included in a system for measuring electrical resistance. When the glove material is stretched or compressed, for example under flexion of knuckle, the distance separating the bared metal tips 340 changes, and there is a concomitant change in electrical resistance.

Although the electrodes 336 are not required to be helical, the helical shape is advantageous in allowing the electrodes 336 to bend and stretch with the rubber layer 334, while preventing the electrodes 336 from slipping from their positions within the layer 334.

It will be appreciated that other arrangements may be used for ensuring that the relative movement between the electrodes 320 and 336 results from stretching the rubber layer 304 and 334, and does not arise from the electrodes slipping within the layer. For example, the end of the electrode 336 close to the metal tip 340 may be anchored in the rubber layer 334 using a collar or the like.

A rubber sensor layer having sensors disposed within the layer as illustrated in Figs. 5.3.a and 5.3.b may be thin, for example 0.5 to 1 mm thick. Such a thin layer advantageously permits the glove to be flexible and reduces any limitations on the range of permissible glove movement.

Also, such a thin layer reduces the weight of the data glove, thus allowing the user to operate the data glove for extended periods of time without undue fatigue.

Figs. 5.5.a and 5.5.b illustrate the application of a helical electrode type sensor to a glove. A sensor strip 500 is shown in Fig. 5.5.a. The sensor strip includes two helical electrodes 502 and 504, having respective bared tips 506 and 508 separated by a distance d. The helical electrodes 502 and 504 are isolated from the environment by the outer and inner layers of the strip 500. A measurement of the electrical resistance across the end points 510 and 512 of the respective helical electrodes 502 and 504 provides a measure of the resistance, and therefore the distance, between the tips 506 and 508. Lateral stretching of the strip 500 in the direction 514 results in an increase in the measured resistance.

Fig. 5.5.b illustrates the formation of a data glove by applying a number of sensor strips to an uninstrumented glove 520. The uninstrumented glove 520 includes four fingers 522, 524, 526, 528, and a thumb 530. Four sensor stripes 532, 534, 536 and 538 are applied to the back of the uninstrumented glove 520 and respective fingers 522, 524, 526, and 528 to produce an instrumented glove. Additionally, a thumb stripe 540 is applied on the back of the glove 520 and the thumb 530. To explain how the data glove works, consider that a user is wearing the glove 520. Flexion of the forefinger 522 results in a change in resistance measured in the respective forefinger stripe 532.
This change in resistance may be detected by a control unit (not illustrated) and identified as a movement of the forefinger 522. Additionally, a transverse stripe 542 may be placed across the back of the glove 520 for detecting abduction, i.e. the spreading of the fingers 522, 524, 526, and 528 relative to one another.

It will be appreciated that each strip 532, 534, 536, 538, 540 and 542 may be provided with more than one sensor to detect motion at more than one position the glove 520. For example, the finger strips 532, 534, 536, and 538 may each be provided with three or more sensors, with at least one sensor being placed on a respective strip to sense the movement of a corresponding finger joint. Thus, the glove may be instrumented to detect motion of each joint, individually and independently. Additionally, the sensors may be disposed on individual strips attached to the glove, or may be disposed on a single layer attached to the glove.

Fig.5.6 illustrates another embodiment of a data glove. The hand 600 is surrounded by an inner glove portion having an upper portion 602 and a lower portion 604. The upper and lower portions 602 and 604 are illustrated to be separated, but it will be appreciated that the inner glove forms a single unit into which the user inserts his or her hand. A supporting layer 606 is disposed on the upper portion 602.

A resistive rubber sensor layer 608 is disposed on the first isolating layer 606. A network of electrical cables 610 makes connections through the sensors in the sensor layer 608, and permits connection to a control unit (not illustrated). A second isolating layer 612 is disposed over the cable network 610. An outer layer 614 may be disposed on the second isolating layer 612. The outer layer may, for example, feature a design or the like indicative of the type of glove or the manufacturer thereof.

It will be appreciated that the sensor layer 608 may include a number of stripes having helically coiled electrodes, or may include laminated sensors as illustrated in Fig. 5.3.a. It will further be appreciated that the sensor layer may be provided on either the dorsal (back) surface of the glove or the volar surface (the palm surface), or both. An advantage of placing the sensor layer on only one surface of the hand is that the other surface may breath through the fabric of the glove, thus increasing the user's comfort.

Fig. 5.7 illustrates one particular embodiment for recording and analyzing data produced by the data glove 700. Data from the data glove 700 are transmitted to a signal recording and conditioning unit 702. The recording and conditioning unit 702 receives resistance data from each of the sensors in the glove 700, and converts these signals into signals representative of the magnitude of extension detected by each sensor. These conditioned signals may then be directed through an interface 704 to a computer 706. The interface 704 may be, for example, an RS232 serial interface. It will be appreciated that the computer 706 may be a PC compatible type computer, Macintosh compatible computer, a UNIX based workstation, or any other type of computer.

The glove 700 may also be provided with a position sensor 710 which determines the position of the glove within a prescribed area, such as a room. A position sensor may be based on the detection of an electromagnetic or ultrasonic signal to determine position within the room. For example, an electromagnetically based sensor may have x, y, and z antennas for detecting x, y, and z, radiated signals. A measurement of the strength of the detected signals provides information on the distance from the transmitters. The position sensor 710 transmits position data through an interface 708 to the computer 706. The interface 708 may be, for example, an RS232 serial interface.

Fig. 5.8 illustrates the degrees of freedom (DOF) of the hand which may be measured using a data glove of the present invention. The figure illustrates four fingers, the index finger, the middle finger, the ring finger, and the pinkie finger, and the thumb. Black dots represent joints between adjacent finger bones. The dots marked 802 represent the joint between the distal phalanx and the middle phalanx of each finger (the distal interphalangeal joints).

The dots marked 804 represent joints between the middle phalanx and the proximal phalanx of each finger (the proximal interphalangeal joints). The dots marked 806 represent the joints between the proximal phalanx and the metacarpal bone of each finger (the metacarpophalangeal joints).

The joint between the proximal phalanx and the distal phalanx of the thumb is marked 812 (the thumb interphalangeal joint), the joint between the proximal phalanx and the metacarpal bone of the thumb is marked as 814 (the thumb metacarpophalangeal joint), and the joint between the thumb metacarpal and the trapezium is marked as 816 (the trapeziometacarpal joint).

The data glove may provide a sensor for detecting flexion of the joint between the distal and middle phalanges of each finger, and also flexion of the joint between the middle and proximal phalanges of each finger. The numbers "1" indicate the number of types of movement detected at specification locations on the hand. Thus, where only flexion is measured, number "1" is shown.

The numbers "2" shown by the joints between the proximal phalanx and metacarpal of each finger 806 indicate that both flexion and abduction of these joints may be measured.

On the thumb, flexion may be measured on the joint between the distal and proximal phalanges 812, and the joint between the proximal phalanx and the metacarpal 814. However, since the thumb is opposable, there are three types of motion which may be measured at the joint between the metacarpal and the trapezium 816.
These movements are flexion, abduction and rotation. Rotation is also known as opposition or circumduction.

Data representing movements at all of these joints may be transmitted to a tracking system. An example of a circuit that may be used in signal acquisition, conditioning and analysis is illustrated in Fig. 5.9. Sensor resistance measurement functions are illustrated under the "signal conditioning" portion, labeled as 900. Signal analysis, including analog to digital conversion, and circuit control functions are illustrated under the "analyzer and control" portion, labeled 902.

The glove is assumed to have a number, n, of sensors 904. Each sensor 904 is connected to a demultiplexer 906 and a multiplexer 908. In one particular embodiment, the demultiplexer 906 and the multiplexer 908 are controlled by a processor 918 to selectively connect one of the sensors 904 with one of a number of measurement resistors 912.

A programmable measurement resistor selector 910 is controlled by the processor 918. The voltage signal across the measurement resistor 912 is indicative of the resistance of the sensor selected by the demultiplexer 906 and multiplexer 908. The voltage signal is fed into an amplifier 914 before being converted to a digital signal in an analog-to-digital converter 916.
The digitized signal is then transferred to the processor for further processing and analysis, or for transferring through an interface 920 to, for example, a computer.

The processor 918 controls the demultiplexer 906, the multiplexer 908 and the programmable measurement resistor selector 910 so as to sample the resistance of the sensors 904, or selected sensors 904, at regular intervals. When the sensor is strained over a large range, the voltage signal fed to the amplifier 914 increases. The processor 918 selects a measurement resistor 912 according to the amount of strain in the sensor 904 being measured, so that the voltage signal fed to the amplifier 914 remains within predetermined limits.

Fig. 5.10 illustrates a "master-slave" method of imaging the movements of a hand. The hand is contained within the data glove 1000, and data from sensors within the glove 1000 are conditioned in a signal conditioner 1002. The data from the signal conditioner 1002 are transmitted over a cable 1004 to an analyzer 1006. Analyzed data are then transmitted over an interface 1008 to a computer 1010. The computer 1010 is connected to a video monitor 1012.

The computer 1010 may be configured to display an image of the hand 1014 that corresponds to the information transmitted from the glove 1000. Accordingly, the image of the hand 1014 may show movements that correspond to movements of the users hand within the glove 1000.
It will be appreciated that the glove 100 may also act as a mast to control a robot hand operating as a slave. The robot hand may be connected to the data glove 1000 through a computer or other electronic circuit, so that the robot hand is controlled to produce movements corresponding to the movements detected by the data glove 1000.

Figs. 5.11.a-11.c illustrate different arrangements for connecting a data glove to a computer. In Fig. 5.11.a, a data glove 1100 is provided with a signal conditioner 1102. The signal conditioner 1102 may be small and positioned on the back (dorsal) surface of the glove 1100 in a position where it causes little or no interference with the movements of the user's hand within the glove 1100. The glove may be provided with a strap 1104, fastener or the like to fit the glove 1100 tightly to the user's hand. A cable 1106 connects the signal conditioner 1102 to a signal analyzer 1108.

The signal analyzer 1108 may include an analog-to-digital converter and a processor. The signal analyzer 1108 is connected through a second cable 1110 to a computer 1112, such as a PC, Macintosh, Unix workstation or the like.

Another arrangement for connecting the data glove 1100 to a computer is illustrated in Fig. 5.11.b. Here, the computer 1124 includes an extension card 1122. The card 1122 includes a signal analyzer 1120 which is connected to the signal conditioner 1102 via the cable 1106.

In another arrangement for connecting the data glove 1100 to a computer, illustrated in Fig. 5.11.c, the signal conditioner 1134 is removed from the glove 1100, and is connected thereto through a cable 1132 and connector 1130. The signal conditioner 1134 is connected via a second cable 1136 to the signal analyzer 1120 on the extension card 1122 within the computer 1124.

Figs. 5.12 and 5.13 illustrate that the data glove may be used as an interface between a user and a computer for operating a computer game. Fig. 5.13 illustrates 8 different gestures that may be made by a hand inside a data glove. Each of these gestures may be associated with a particular instruction for a computer game. For example, a gesture in which the thumb and index finger are extending and the remaining fingers are folded may be used to represent an instruction to move forwards (gesture a)). A gesture in which the thumb and the index and middle fingers are extending may be used to represent an instruction to move backwards (gesture b)).

The gestures have nothing to do with the robotic hand. They just illustrate that this part of the program can be used very nicely for the game industry and shall be adapted to different games of Microsoft.

A gesture in which the middle and ring fingers are folded and remaining fingers and thumb extending may be used to represent movement in one direction, for example, the right (gesture c)). A gesture in which all the fingers except the ring finger are extended, along with the thumb may represent an instruction to move to the left (gesture (d)). A gesture in which all fingers and the thumb are extended, except for the ring finger, may represent an instruction to rotate to the right (gesture e)). A gesture in which all fingers and the thumb are extended, except for the index finger, may represent an instruction to rotate to the left (gesture f)). A gesture in which all four fingers are extended and the thumb is folded may represent an instruction asking for help (gesture g)), and a gesture in which all fingers are folded and the thumb is extended may represent an "OK" command (gesture h).

It will be appreciated that various other gestures may be made by a hand wearing a data glove, and that these gestures may be used to represent additional commands. It will also be appreciated that the correlation between gestures and commands shown in Fig. 5.13 may be different.

Such a range of commands may be used to control a computer game such as is shown in Fig. 5.12, in which the user sees a screen 1200 which shows a virtual world having a number of different walls 1202 that create a virtual maze through which the user has to negotiate. A bar 1204 at the bottom of the screen illustrates a number of gestures associated with different commands. The bar 1204 on the lower edge of the screen 1200 may include a window 1206 that illustrates the current gesture detected from the glove. It will be appreciated that many computer games in which the user has to supply control commands to the computer may be controlled through the use of a number of gestures detected from a data glove.

Figs. 5.14.a and 5.14.b illustrate statistical analyses of a number of gestures performed by a user over a period of time. For each graph, a user repeatedly performed the gestures illustrated in Fig. 5.13. The individual gestures were logged by a computer and a tally of how many times the user performed each gesture was kept. Fig. 5.14.a illustrates a cumulative total of the number of each type of gesture after 10, 20 30 etc. seconds. For example, after 50 seconds, the user had made approximately 425 gestures of type a), 370 gestures of type b) and less than 10 gestures of type c). After 90 seconds, the user had made gesture a) approximately 720 times, gesture b) approximately 490 times and gesture c) approximately 90 times. Fig. 14.b illustrates the number of each type of gesture performed by the user in different 30 second intervals. For example, in the first interval of 30 seconds, the user performed 200 a) gestures and about 40 b) gestures, while in the second interval he performed about 230 a) gestures and about 330 b) gestures.

The information developed by the data glove and illustrated in Figs. 5.14.a and 5.14.b may be useful for determining the physical performance of someone performing a critical task, such as an astronaut or a soldier. For example, a supervisor or supervising computer may monitor the movements of a particular individual performing a task. The different types of movements, or gestures, may be logged and compared to a reference dataset previously acquired for that individual, in which the individual's state of fatigue is correlated with the number of times different movements or gestures have been performed. Once the actual number of movements approaches a number previously determined to indicate that the individual is becoming fatigued, then the commander or controlling computer may indicate to the individual that it is time to rest.

In illustration, it may have been previously determined in control experiments that the individual is able to perform no more than 350 gestures of type e) in a 30 second period without any significant fatigue occurring. However, in the fourth 30 second period shown in Fig. 5.14.b, it is seen that the individual performs almost 450 e)-type gestures. Thus, the individual may be warned after the fourth 30 second period to take a rest because fatigue is likely to occur.

It will be appreciated that the motion of many different body parts may be detected and analyzed using sensors of the type disclosed herein. For example, rather than a glove, the user may wear a sleeve to detect movements of the elbow, or a shoulder harness to detect movements of the neck and shoulders. Sensors of this type may be fabricated to fit almost all of the moveable body parts, including but limited to fingers, hands, wrists, elbows, shoulders, neck, torso, hips, knees, ankles, feet and toes. It is also possible to combine sensors for different parts of the body. For example, a whole body sensor suit may monitor the movement of ankles, knees, hips, torso, shoulders, elbows and wrists, or may include sensors to monitor motion of another combination of body parts. Such a suit fits tightly over the selected body parts so that the sensors remain in place relative to the particular joints, limbs etc. that are to be monitored. For example, such a suit may be worn by an astronaut to allow mission control to monitor the astronaut's progress and movements during an exacting spacewalk mission.

Comparison of the astronaut's movements with reference data taken from control experiments may indicate to doctors or mission control specialists when the astronaut is likely to become fatigued and, therefore, less effective.

While various examples were provided above, the present invention is not limited to the specifics of the examples. For example, the glove fitting around the hand may not be a full glove, but may have only partial fingers, for example extending from the hand to the second knuckle. The use of such a partial glove permits a user to sense movement of a reduced number of finger joints.

As noted above, the present invention is applicable to a glove for detecting motion of fingers and the thumb of a hand. While having use in many different applications, it is believed to be particularly useful for controlling computer games.

Accordingly, the present invention should not be considered limited to the particular examples described, but rather should be understood to cover all aspects of the invention as fairly set out in the attached claims. Various modifications, equivalent processes, as well as numerous structures to which the present invention may be applicable will be readily apparent to those of skill in the art to which the present invention is directed upon review of the present specification. The claims are intended to cover such modifications and devices.

Technical Specification of the "DAUMGLOVE"

Description

The "DAUMGLOVE" measures the motions of the fingers and the thumb. The converted data is transferred to a computer or another master system. The boss of the process is a microcontroller. These data can be implemented into each software one wishes.

Measuring

The "DAUMGLOVE" mesuring is based on flexible stretch sensor patented by Daum. Detection of all finger movements as follows:

angles of the phalanxes	10° of freedom
abduction of the fingers	3° of freedom
rotation of the thumb	3° of freedom

Sensor resolution:	0.5° (8 bit)
Communication interface:	RS232 with selectable baud rates
Power requirements:	Europe: 220 VAC, 50 Hz
	USA: 110 VAC, 50 - 60 Hz
	self-selecting
Weight per glove:	approx. 100 g
Size:	one size fits most
Application:	Game control, navigation in vr - worlds, simulation of work cycle

6. SYSTEM

System is shown in the photograph of fig. 6.1 and in the attached video. It can be seen that the dataglove directly controls the robot hand. Time delay is due to slow electronics and trial and error solution of the sensing mechanism of the dataglove. In further research these two disadvantages have to be overcome.

All details are described in the text. Therefore we do not describe again the system as a whole. In the video can be seen:

1. Shape memory fingers and shape memory tweezer
2. robotic hand system as it is today
3. View through the robotic system, through the endoscope in an artificial body
4. Different structures of robotic hands, which have not been described in this text, but have been developed under Grant DAMD 17-94-J-45-02. This text just describes the interesting main parts and achievements of the program. The in-between-steps with all the different robotic hands are not shown since they have been replaced by the newest version. If it is required to get more detailed information about these hand structures, we are more than happy to hand out more detailed information about these to DARPA.
5. Palpation experiment as described in chapter 3.e
6. DataGlove as it can be used for the game industry.

Since we have listed the program in a previous annual report we will not again print out the program text here. We will be more than happy to hand out all software text and programs to DARPA if this is required.

7. SOFTWARE

Software for robot hand completes following functions:

- manuel balance of particular channels (balance of initial and end values of the fingers)
- automatic calibration of the fingers of the Robot hand
- adjustment of all axes to an analog nominal value
- adjustment of all axes to an analog nominal value and memorization of values
- reproduction of memorized values in form of movements
- Robot hand communication software with physical communication interface and transport interface, e.g. communication with the Daum Glove over the Port COM2. In this function, the Port COM1 sends a communication control protocol from Port COM2.

You can download the software in the RAM (IC9, IC10) as an Intel hex.file and start the programm at adress 1000H with go 1000. In the EPROM IC8 is located a multiprogram to load, save and control files of the controllersystem.

Fig. 7.1 shows the interrupt routine for the fingerposition system with start and stop pulse for the stepper motors. This interrupt routine is the most important part for fast fingermovement without delay between input (digital or analog) and fingermovement. This routine is repeated for all fingers.

8. PATENT REPORT

Two patents have been filed in the United States and Germany regarding

1. the robotic hand structure	09/900,059
2. the DataGlove	08/912,029

Patents are attached to the report.

The U.S. government has a nonexclusive, nontransferrable, irrevocable paid-up license to practice or have practiced these inventions for or on its behalf as provided for by the terms of Grant number DAMD 17-94-J-45-02 awarded by the U.S. Department of the Army.

10. LIST OF PERSONNEL

Wolfgang Daum
Axel Winkel
Patrick Scherr
Guido Pantel
Jörn Husert
Thomas Günther
Hai Hildebrandt
Christian Herrmann

10. APPENDIX 1, DRAWINGS, FIGURES AND PHOTOS

Drawings	3.a.1	to	3.a.6	
	3.b.1	to	3.b.18	
	3.c.1	to	3.c.33	
	3.d.1	to	3.d.19	
	3.e.1	to	3.e.22	
	3.f.1	to	3.f.5	
	4.1	to	4.8	
	5.1	to	5.14	
	6.1.a	and	6.1.b	(photos)
	7.1.			

11. APPENDIX II, PATENT APPLICATIONS

RobotHand	09/009,059
DataGlove	08/912,029

12. CONCLUSION

It has been demonstrated that a small robotic hand working with Bowden pulleys and SME shape memory elements is possible below the range of 10 mm in diameter and movement of nearly 3 Hz speed. The robot hand can be sterilized and used for medical applications and can easily carry up to 400 g of weight. It can be made adaptable to different software and electronic systems and can be pushed through standard surgical trocars. Time delays are still in the acceptable range. Such a robot hand can be controlled by means of a dataglove. It has been demonstrated that a dataglove can easily be manufactured with resistive rubber. Time delay of that resistive rubber is still five times longer than time delay of robotic hand. Both together, robotic hand and dataglove comprise a total time-delay which should be acceptable for standard surgical procedures. Robot Hand with dataglove is precise in the range of a fifth of a millimeter. We propose to test the robot hand now on different surgical robotic systems.

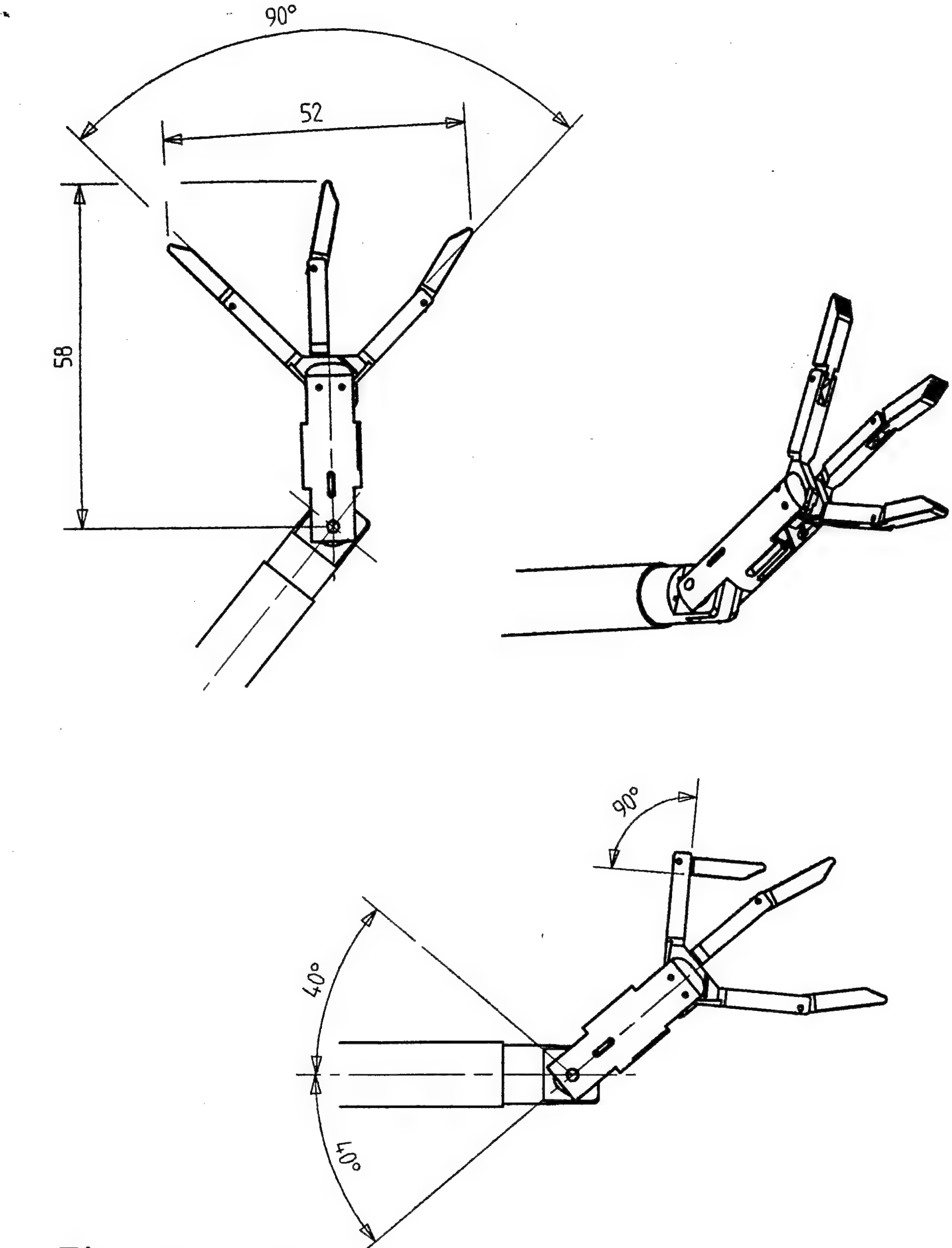

Fig. 3.a.1.a

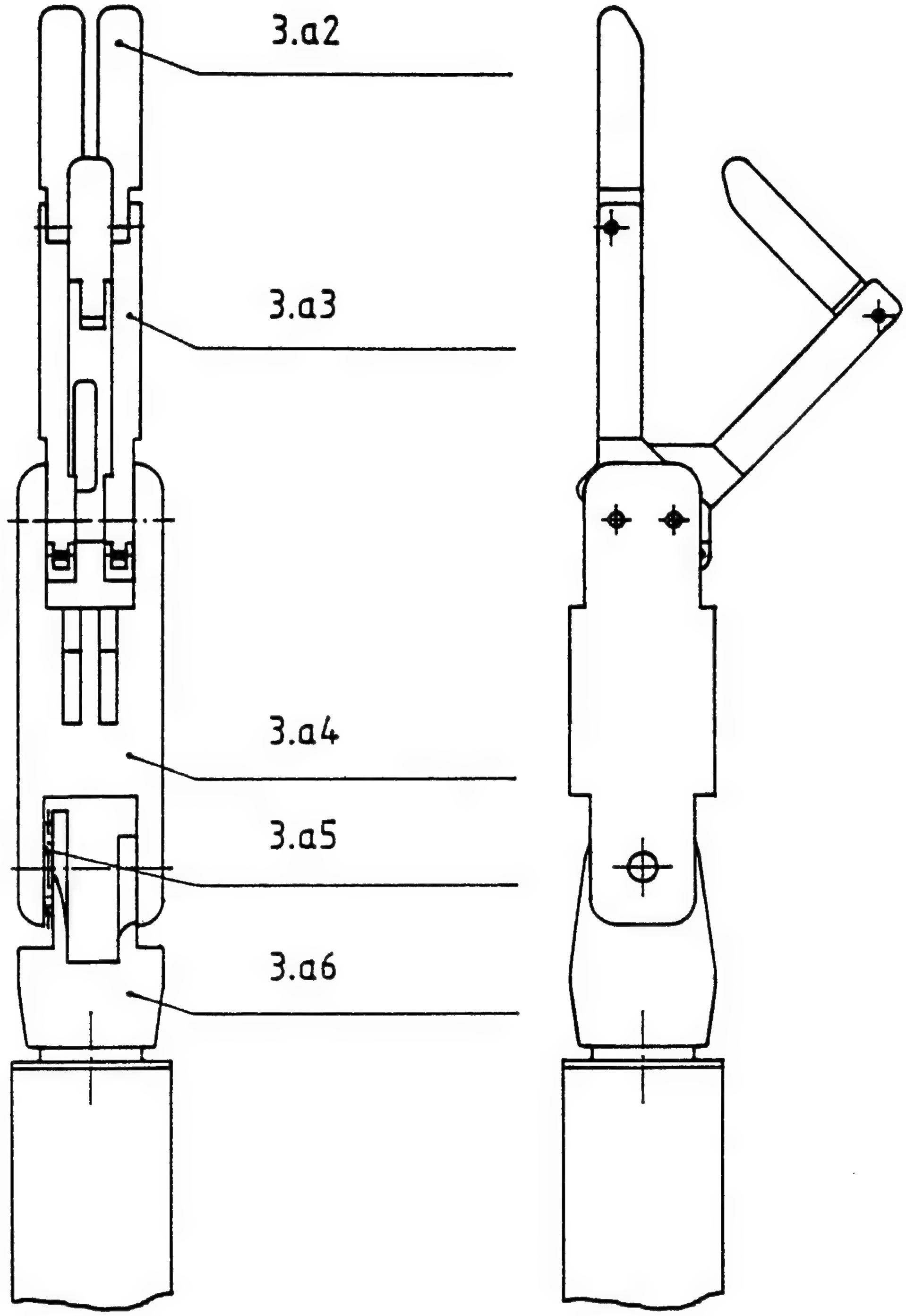

Fig. 3.a.1.b

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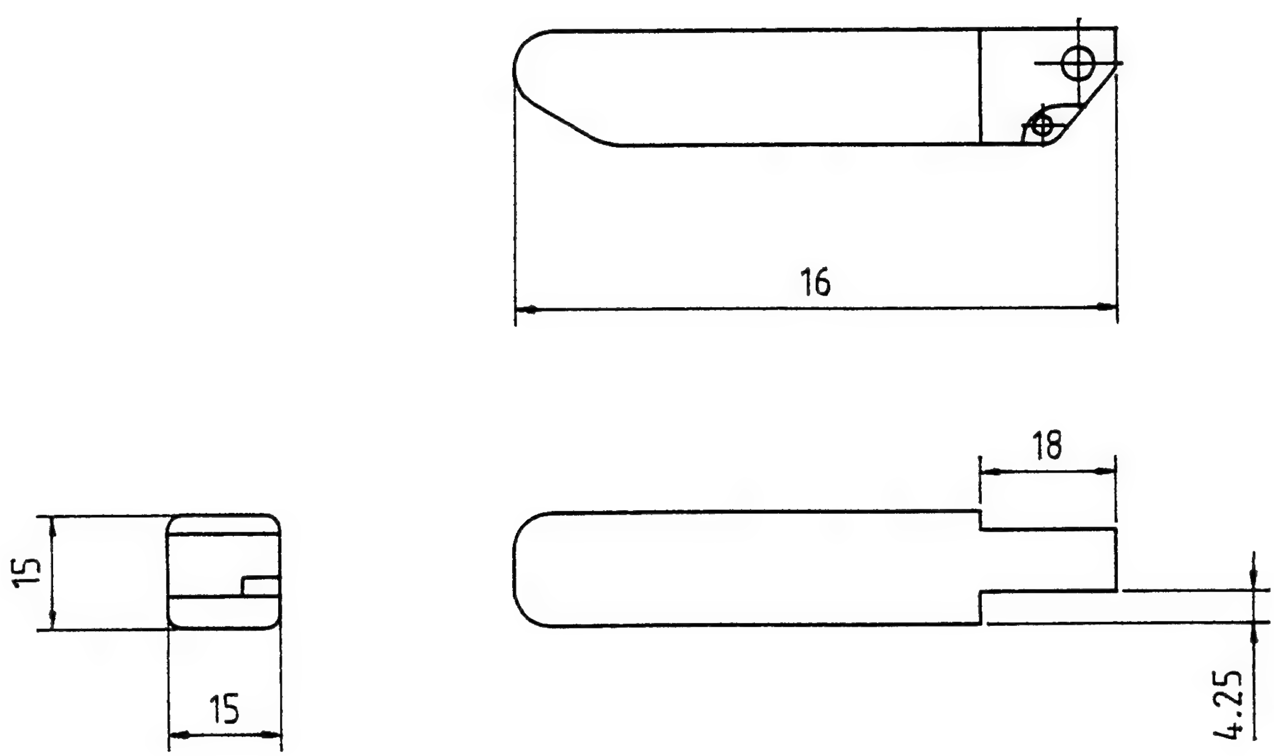

Fig. 3.a.2

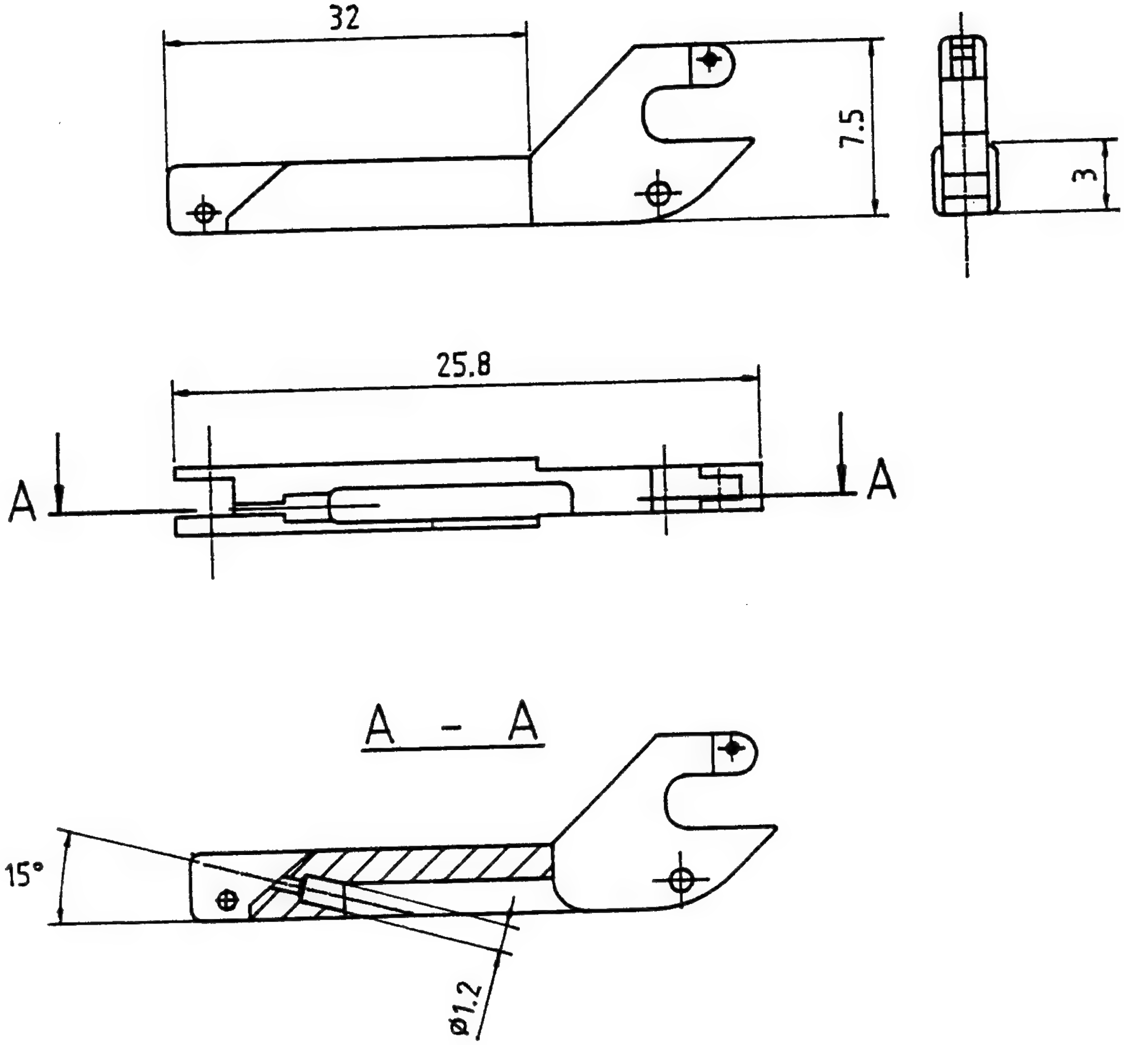

Fig. 3.a.3

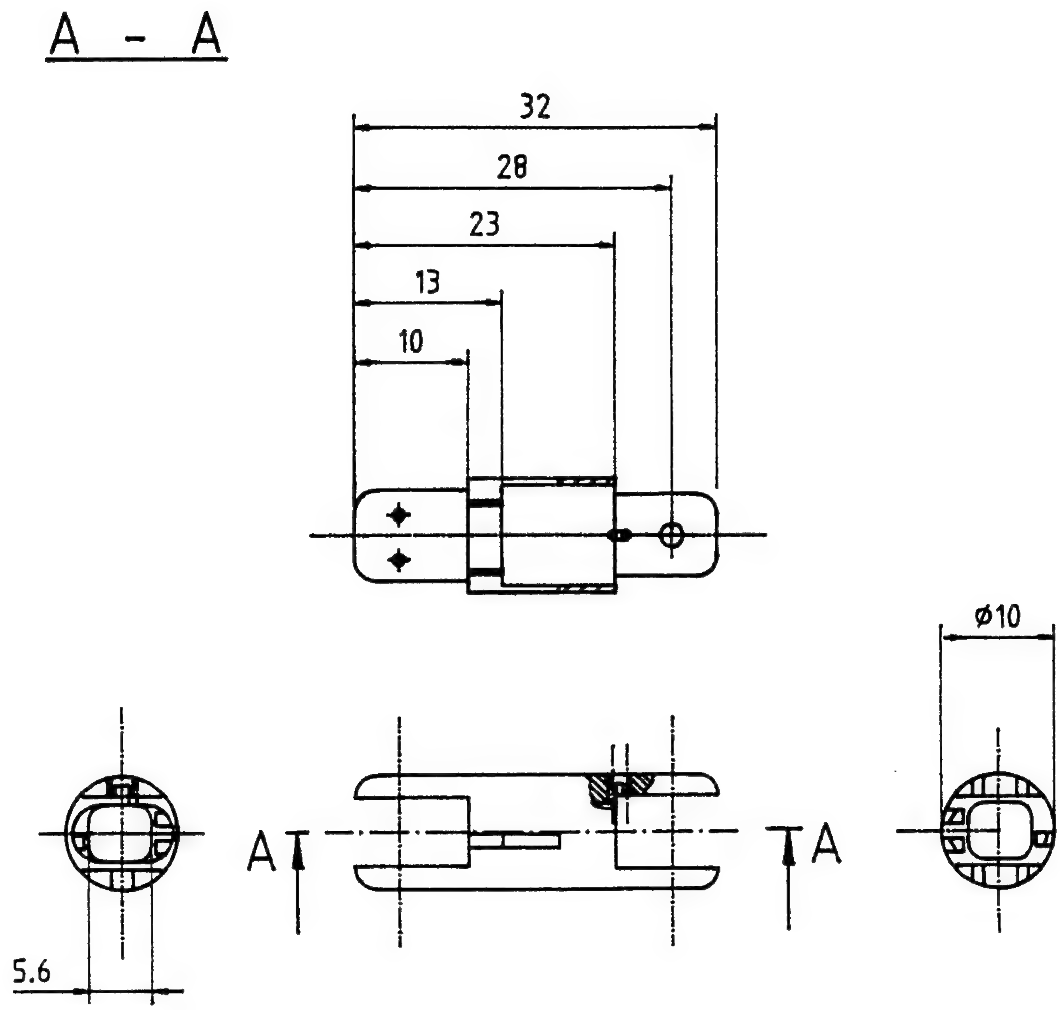

Fig. 3.a.4

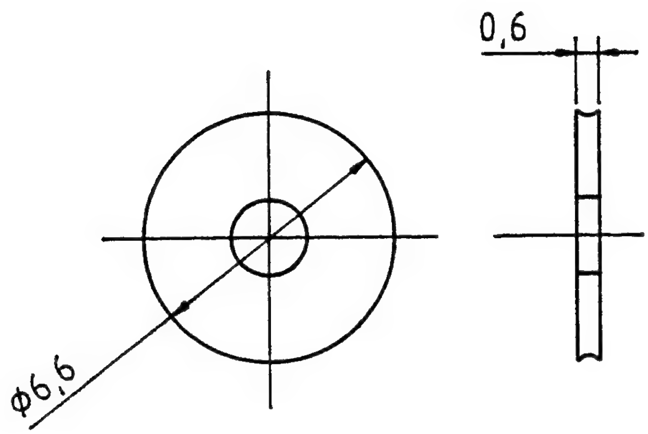

Fig. 3.a.5

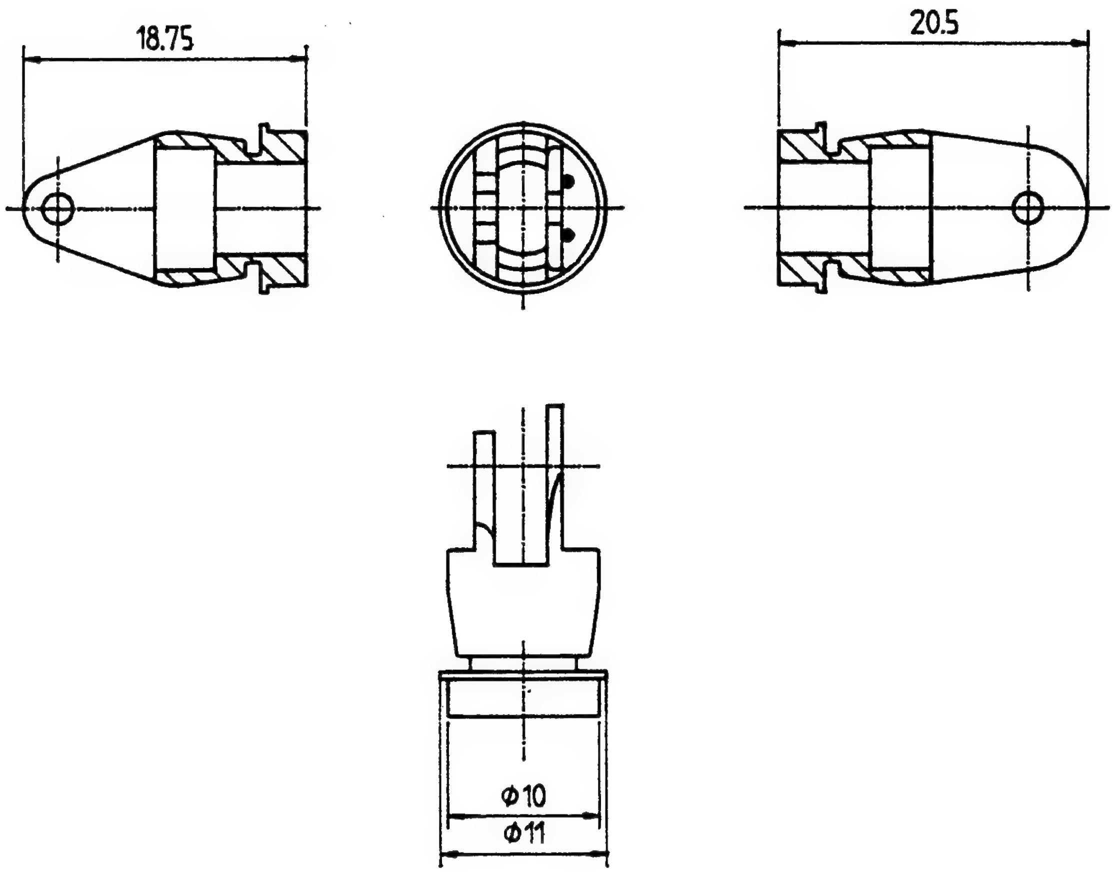

Fig. 3.a.6

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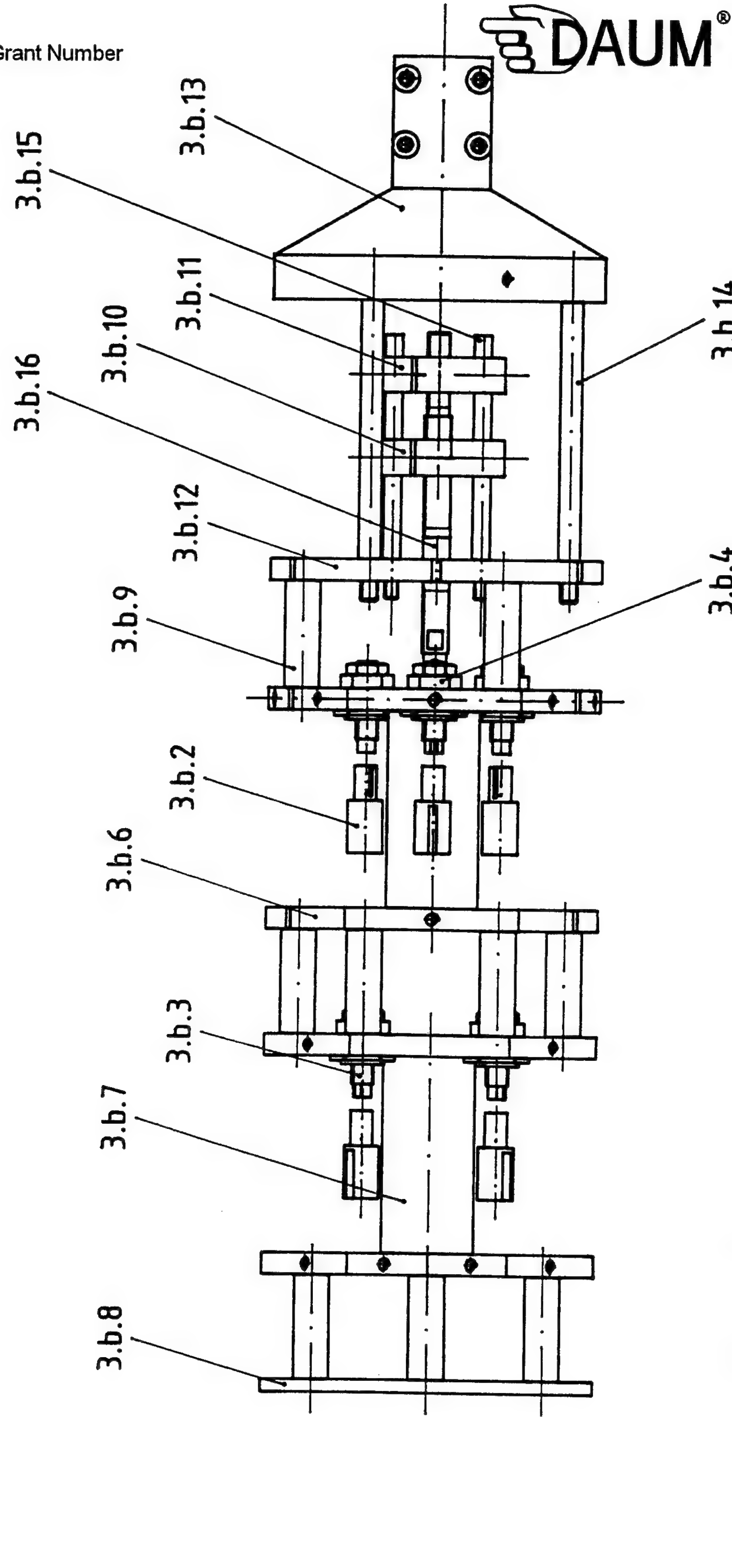

Fig. 3.b.1

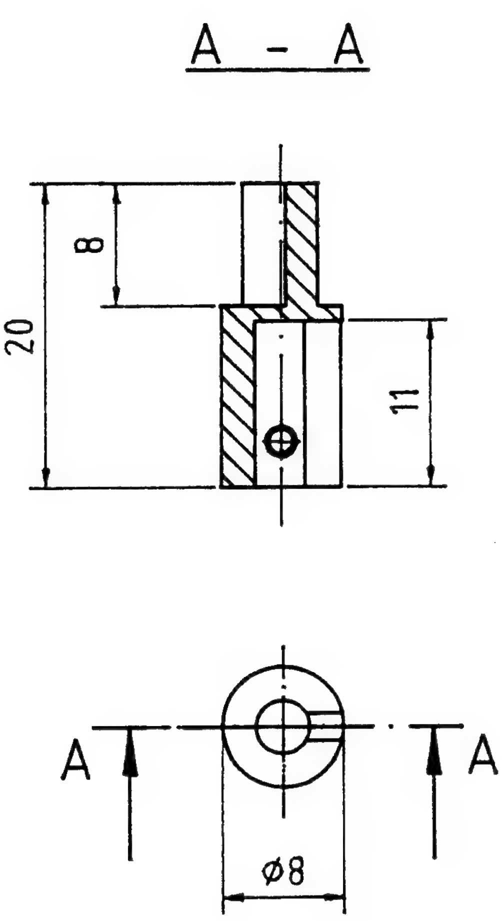

Fig. 3.b.2

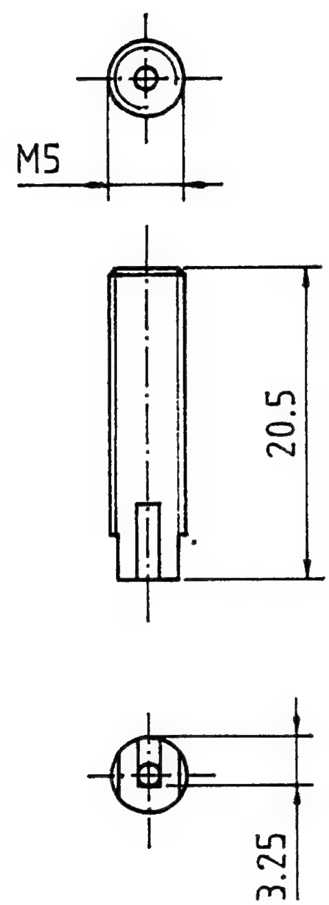

Fig. 3.b.3

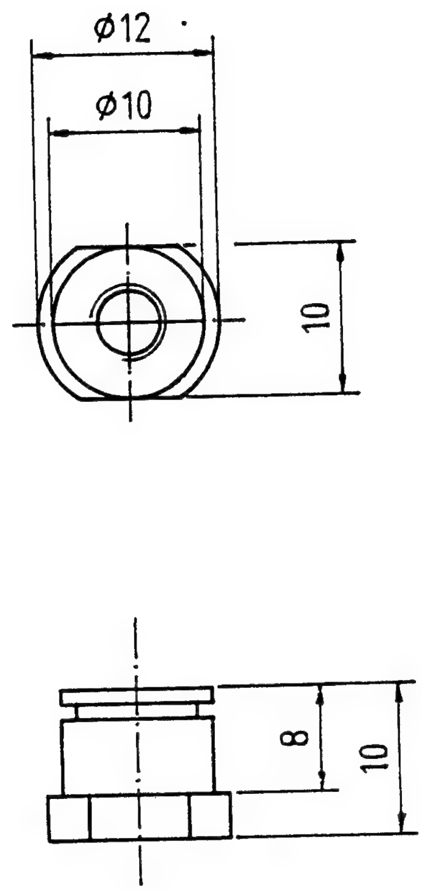

Fig. 3.b.4

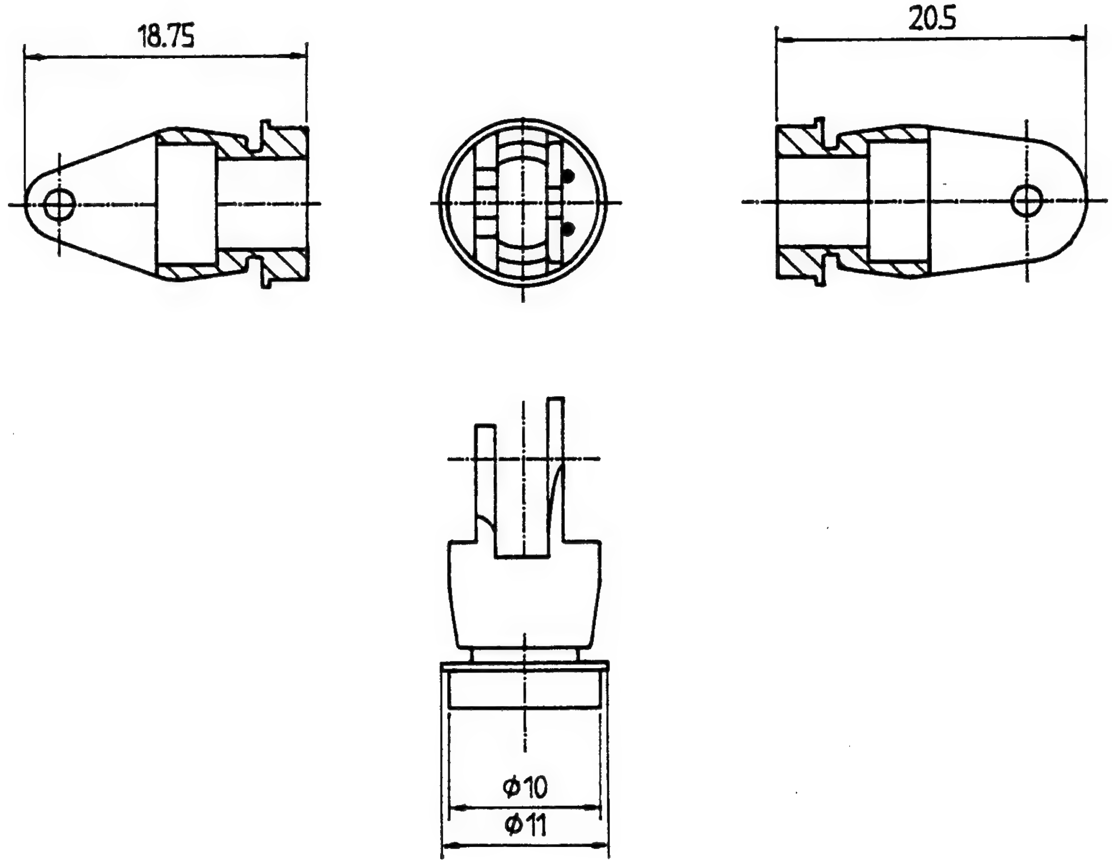

Fig. 3.b.5

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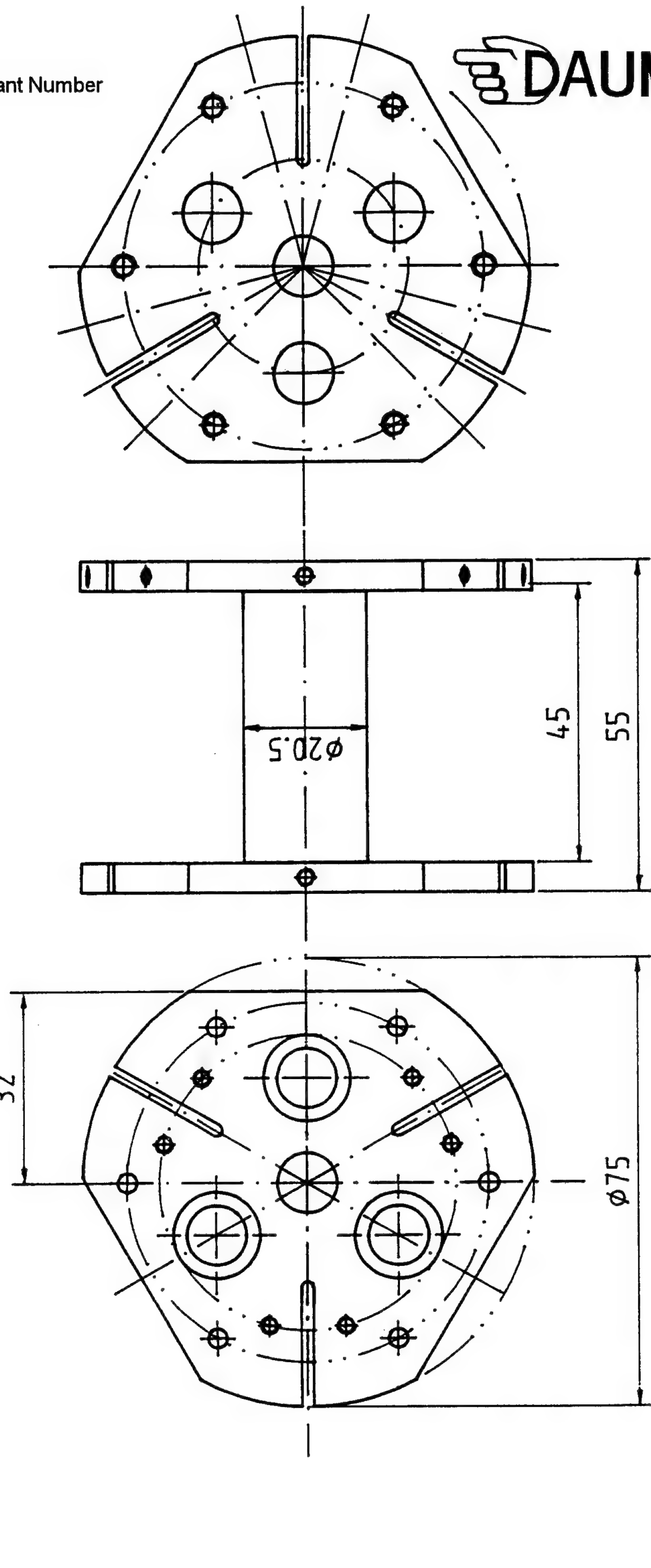

Fig. 3.b.6

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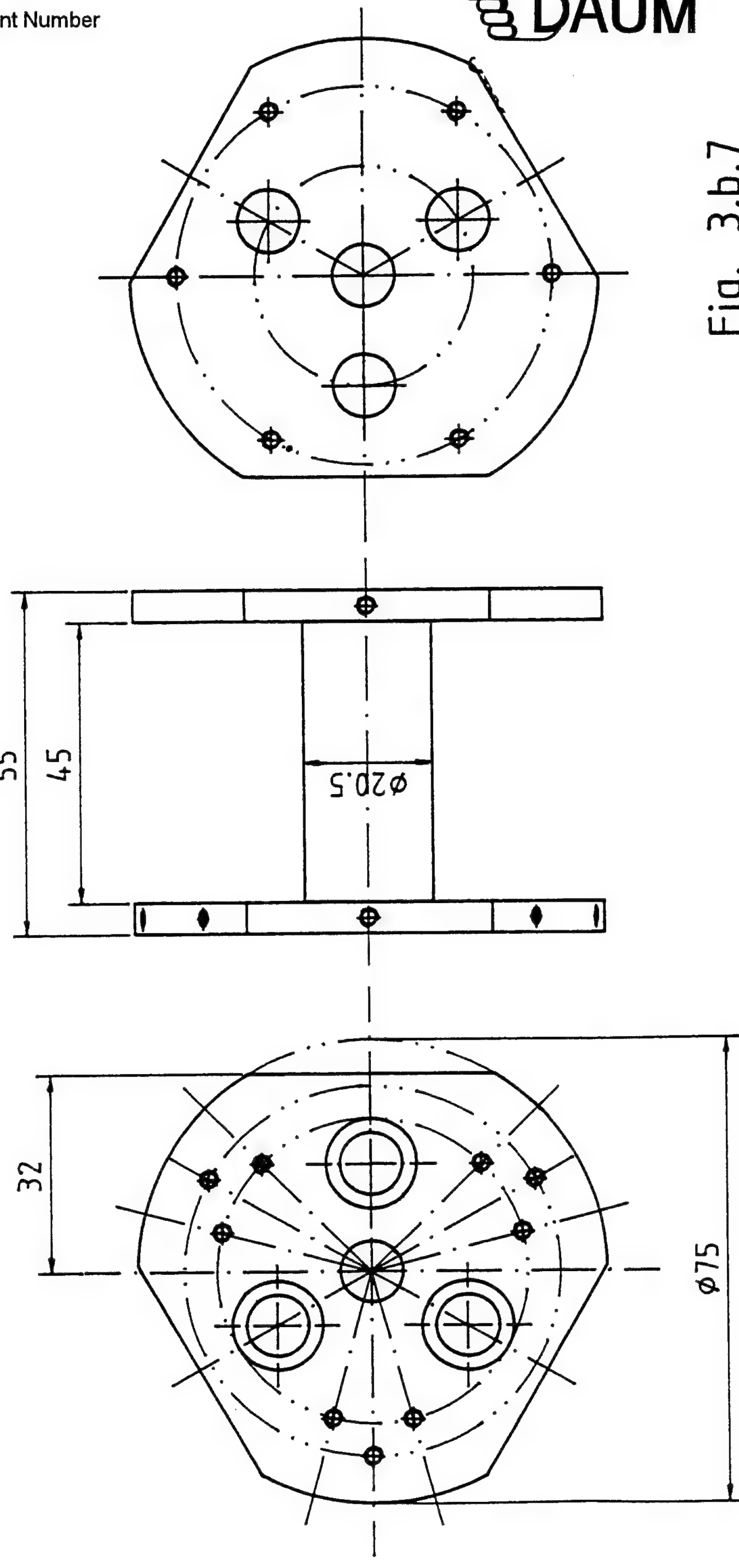

Fig. 3.b.7

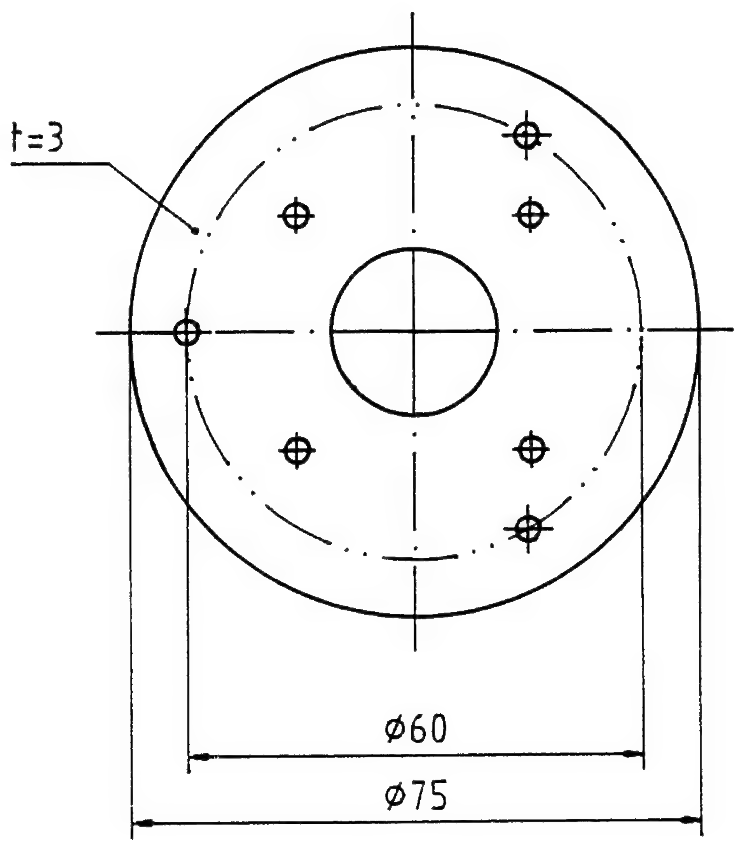

Fig. 3.b.8

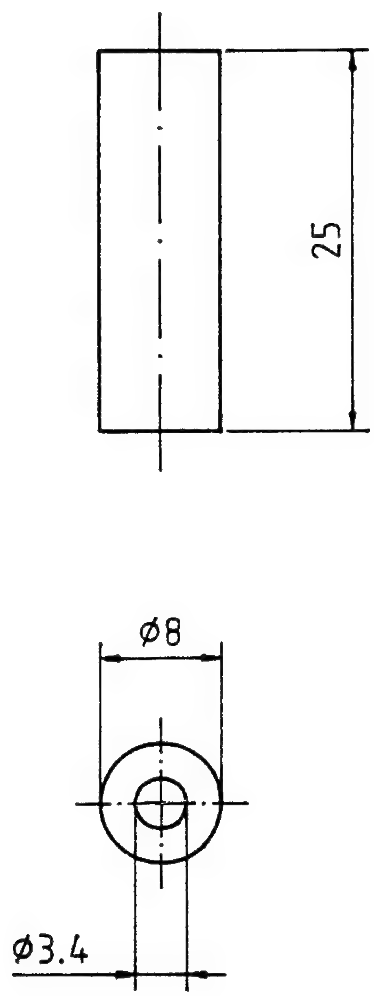

Fig. 3.b.9

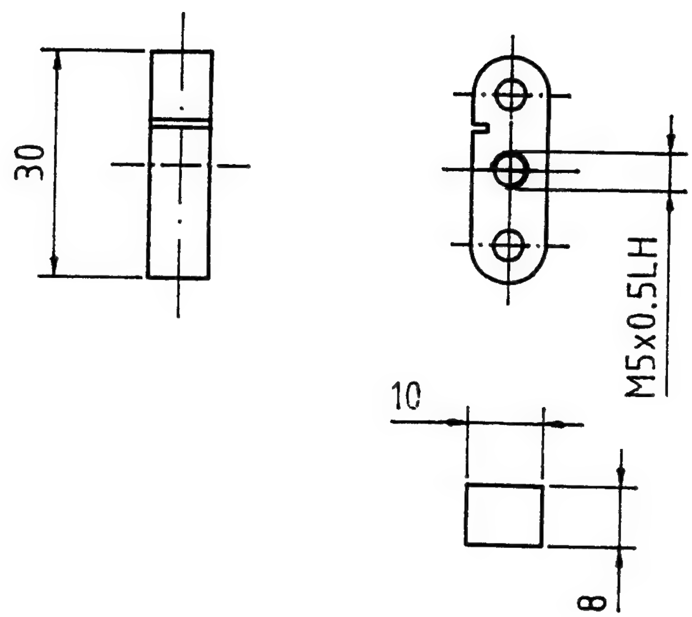

Fig. 3.b.10

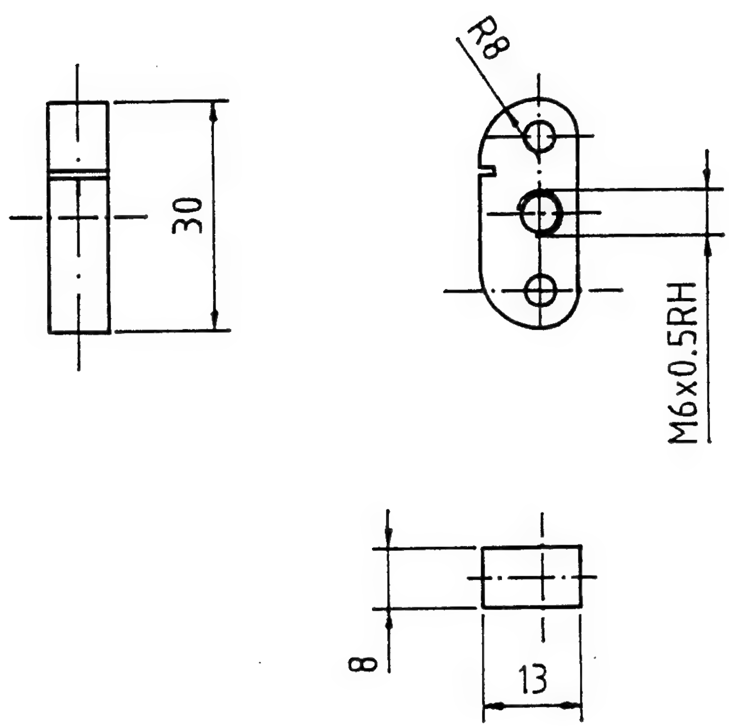

Fig. 3.b.11

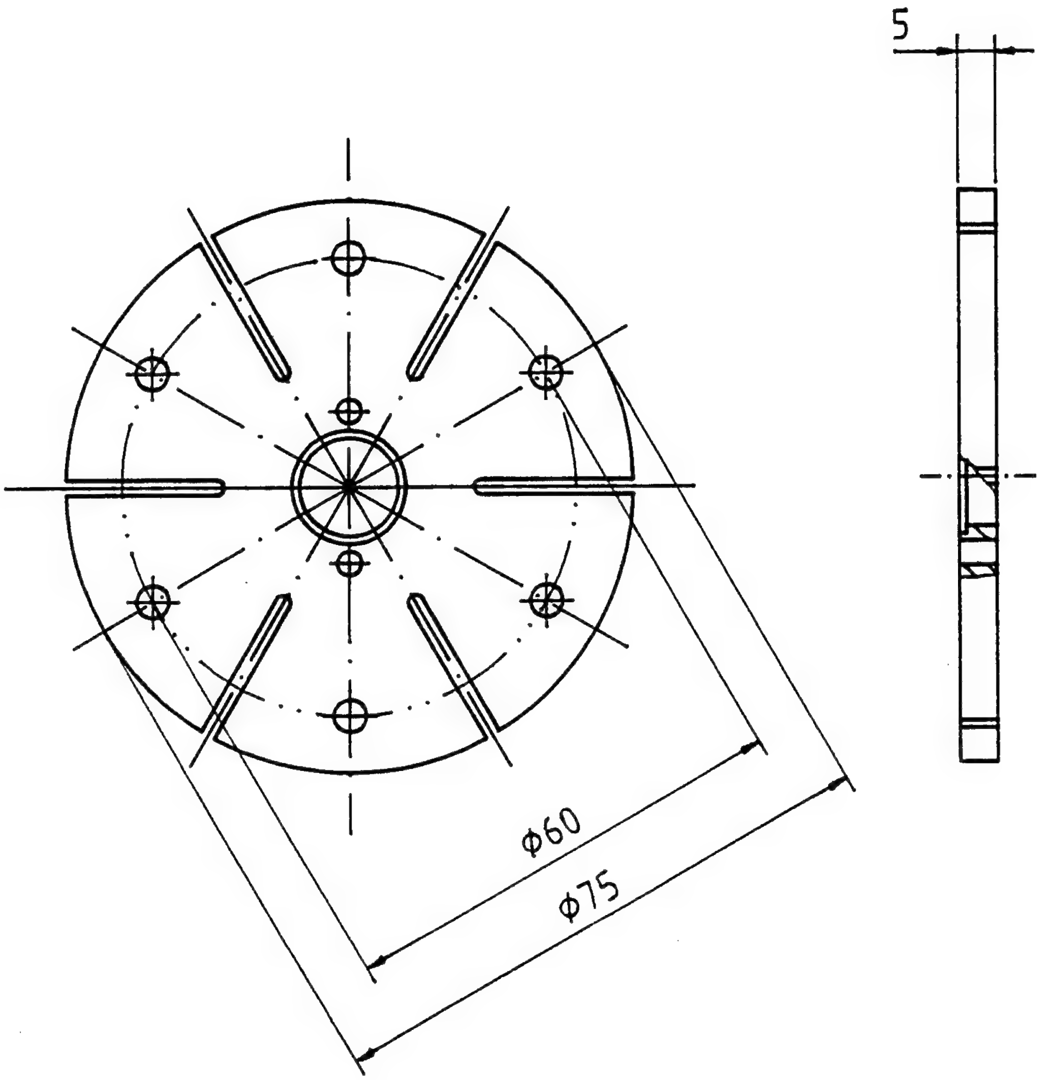

Fig. 3.b.12

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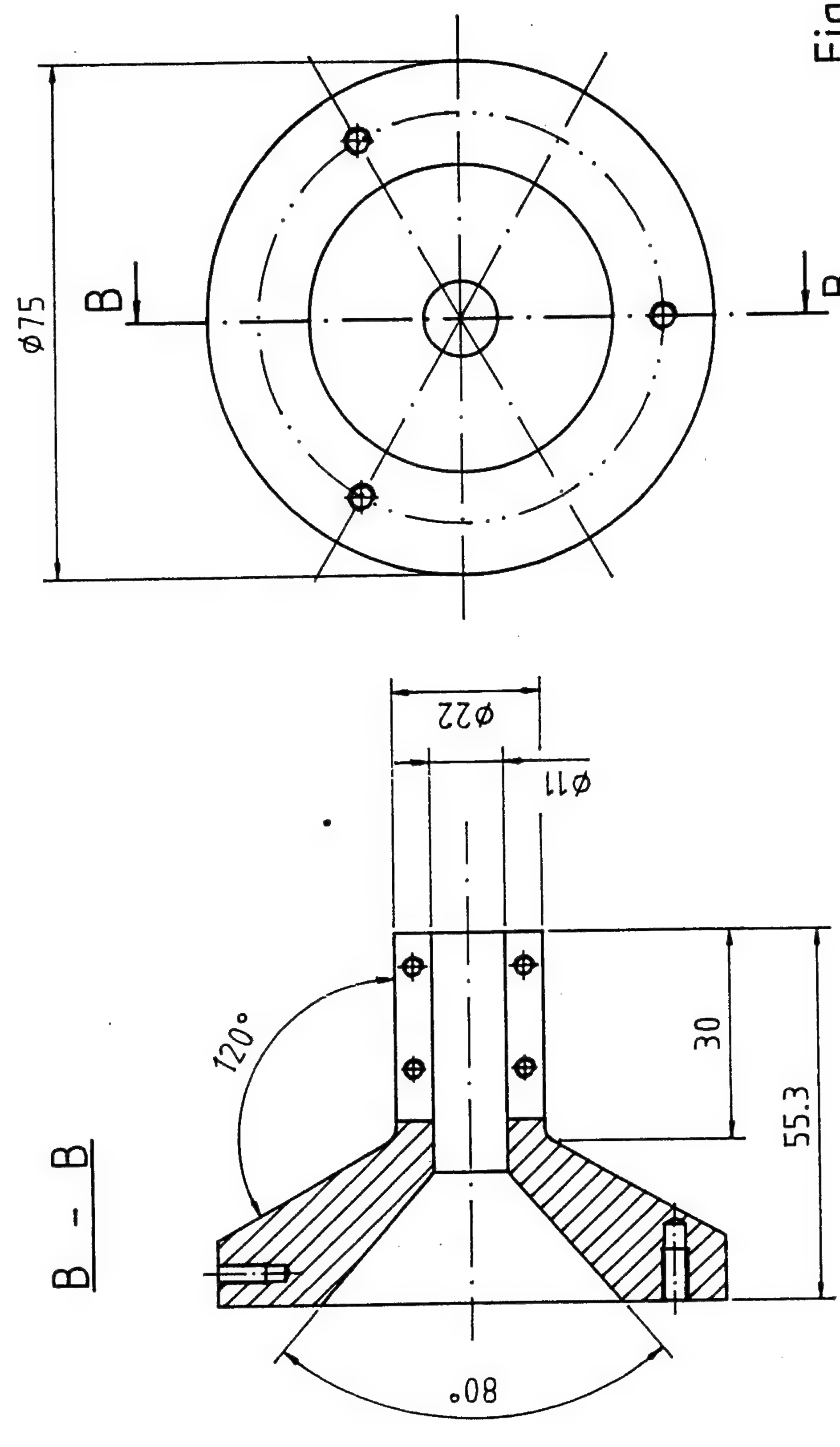

Fig. 3.b.13

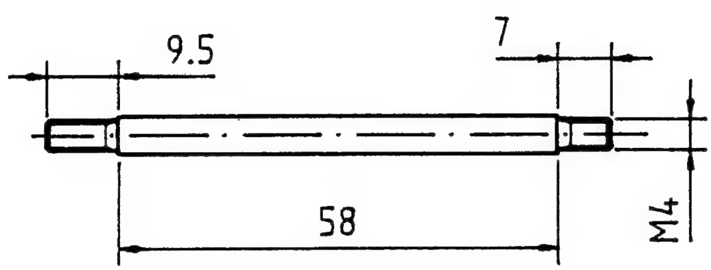

Fig. 3.b.14

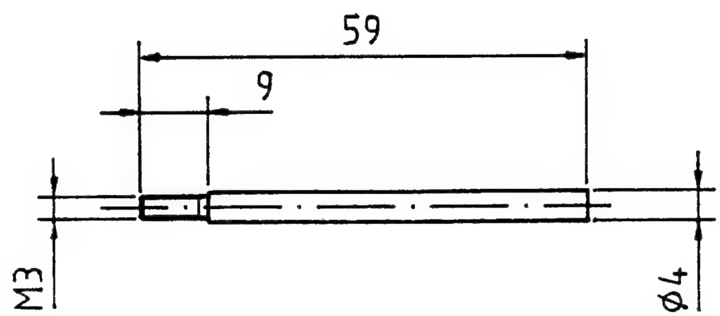

Fig. 3.b.15

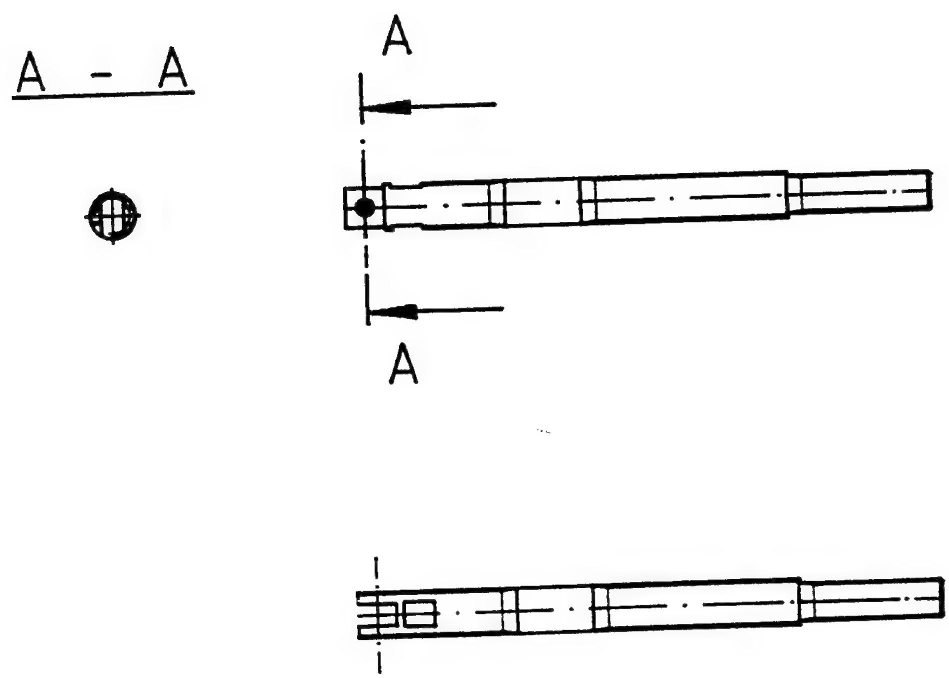

Fig. 3.b.16

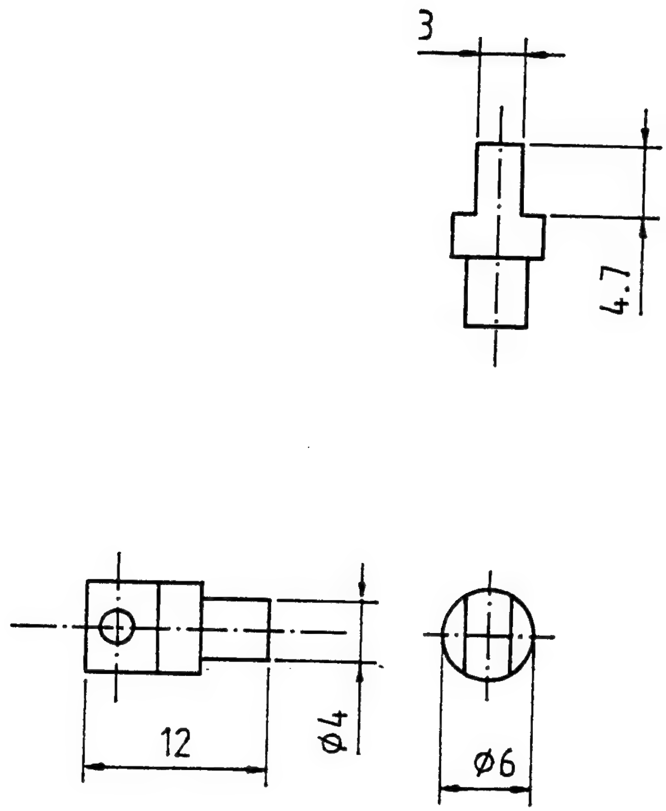

Fig. 3.b.17

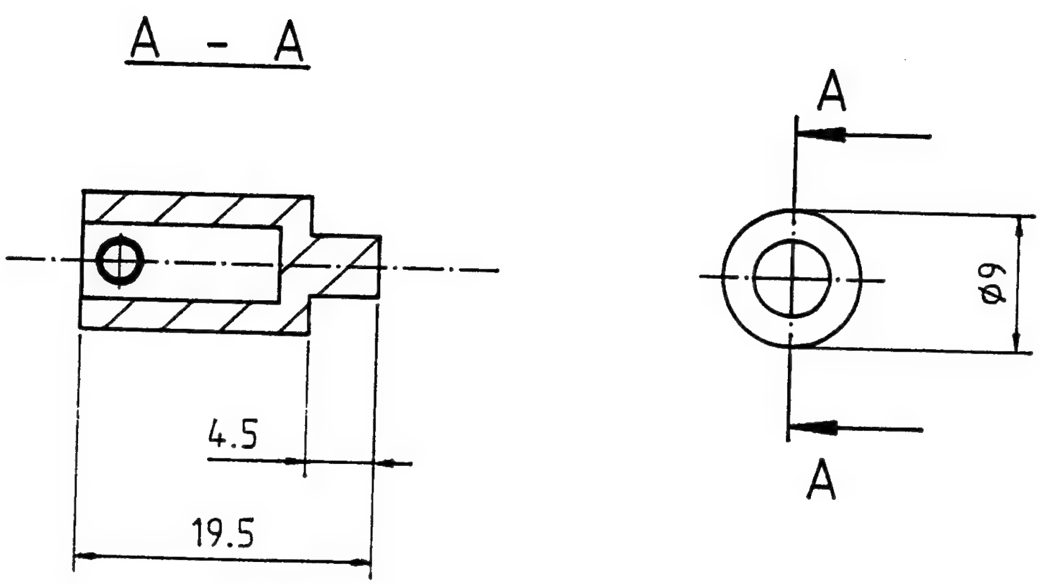

Fig. 3.b.18

Temperature-way-characteristic of CuZnAl bending element (Measurement series taken during first thermal cycle)

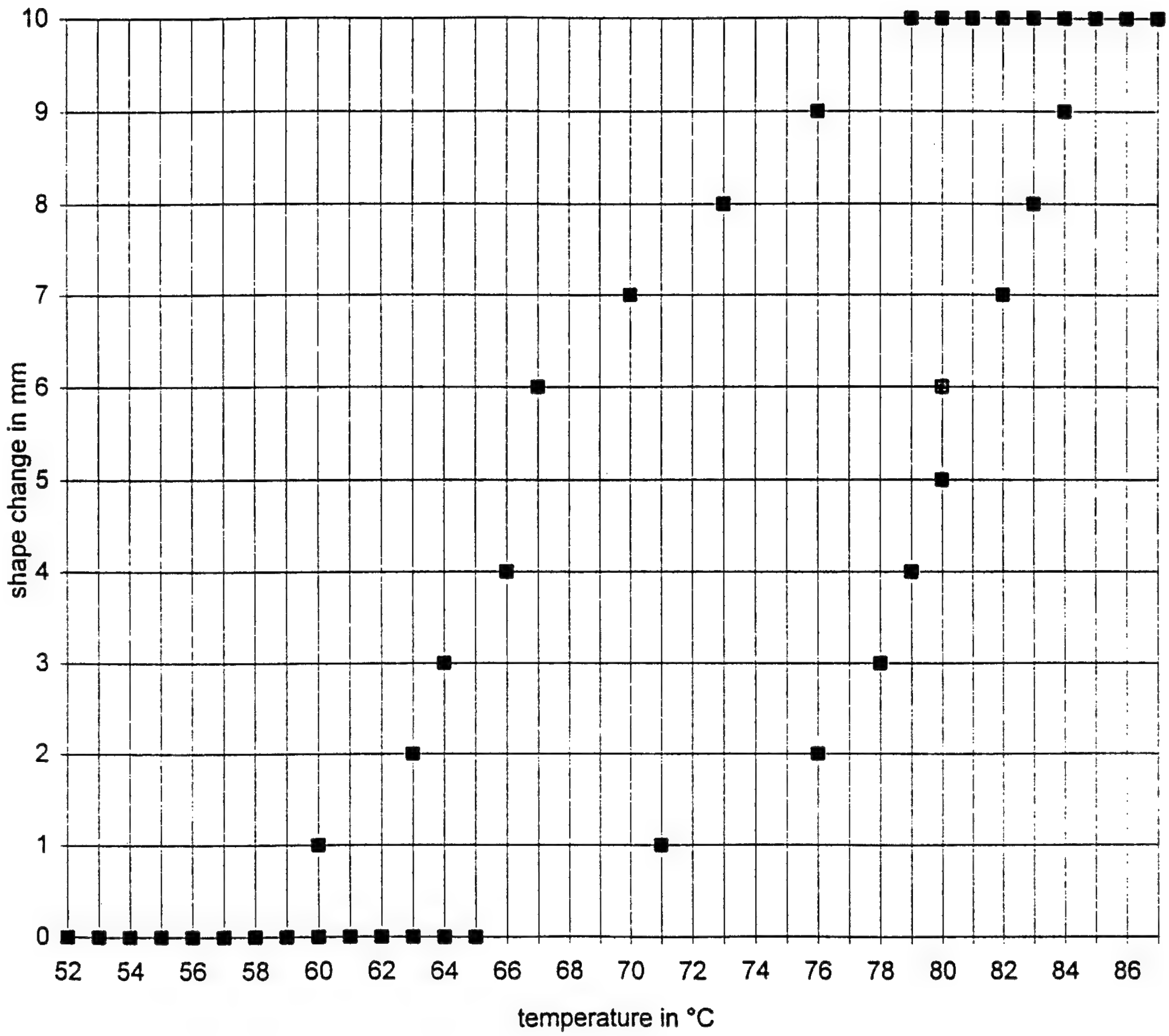

Fig. 3.c.1

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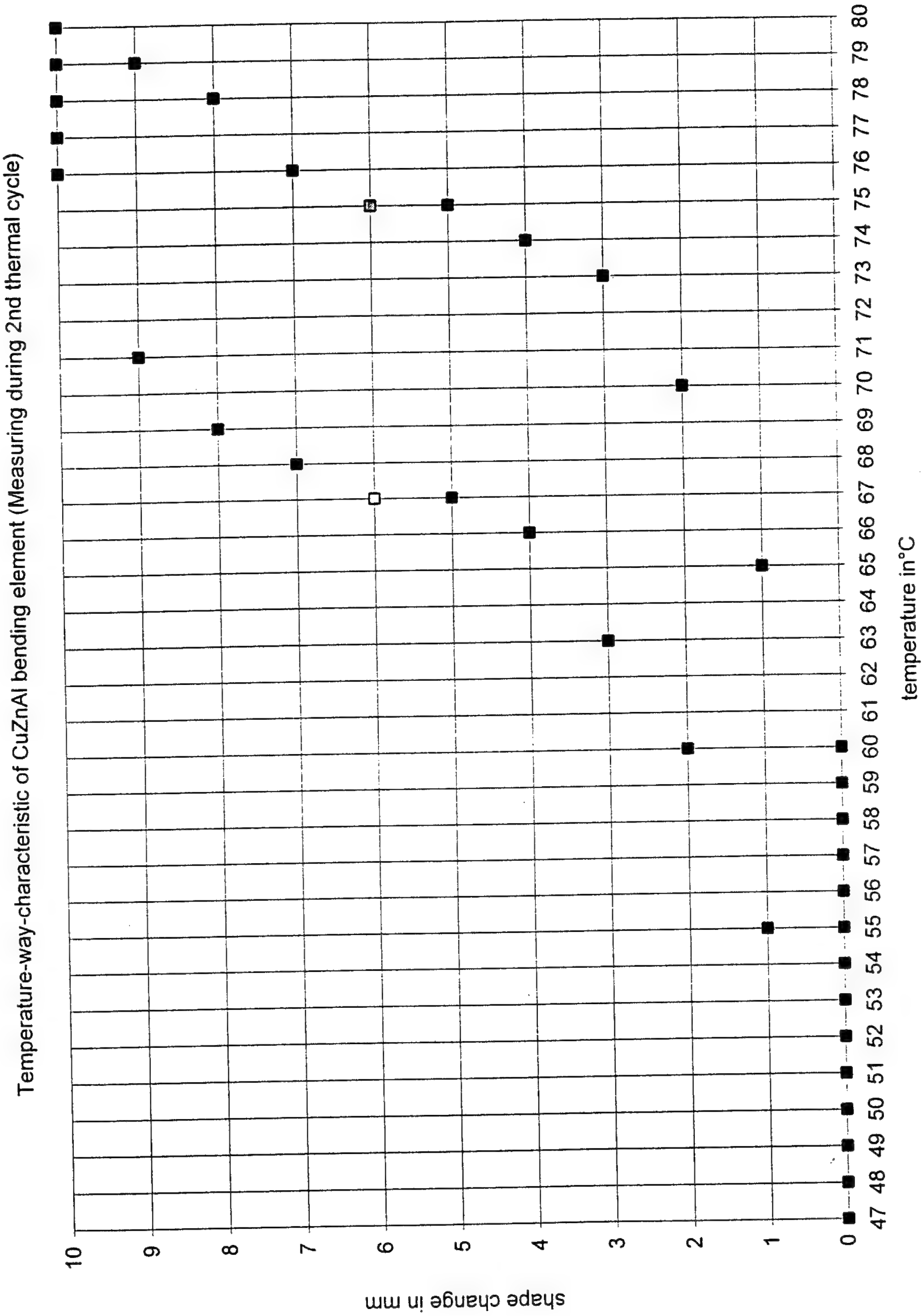

Fig. 3.c.2

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Temperature-Way-characteristic of CuZnAl bending element (Measuring during 2nd thermal cycle

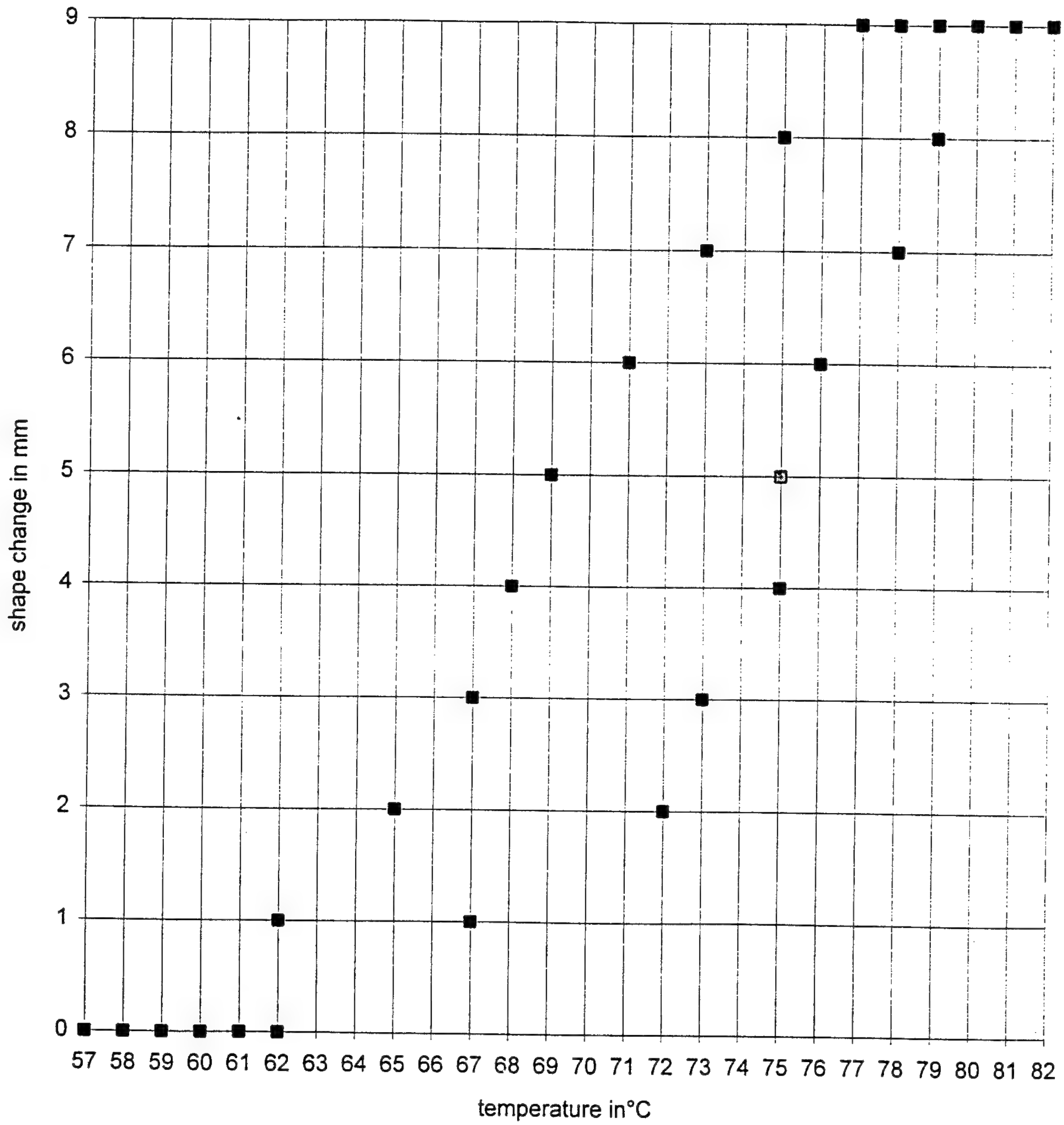

Fig. 3.c.3

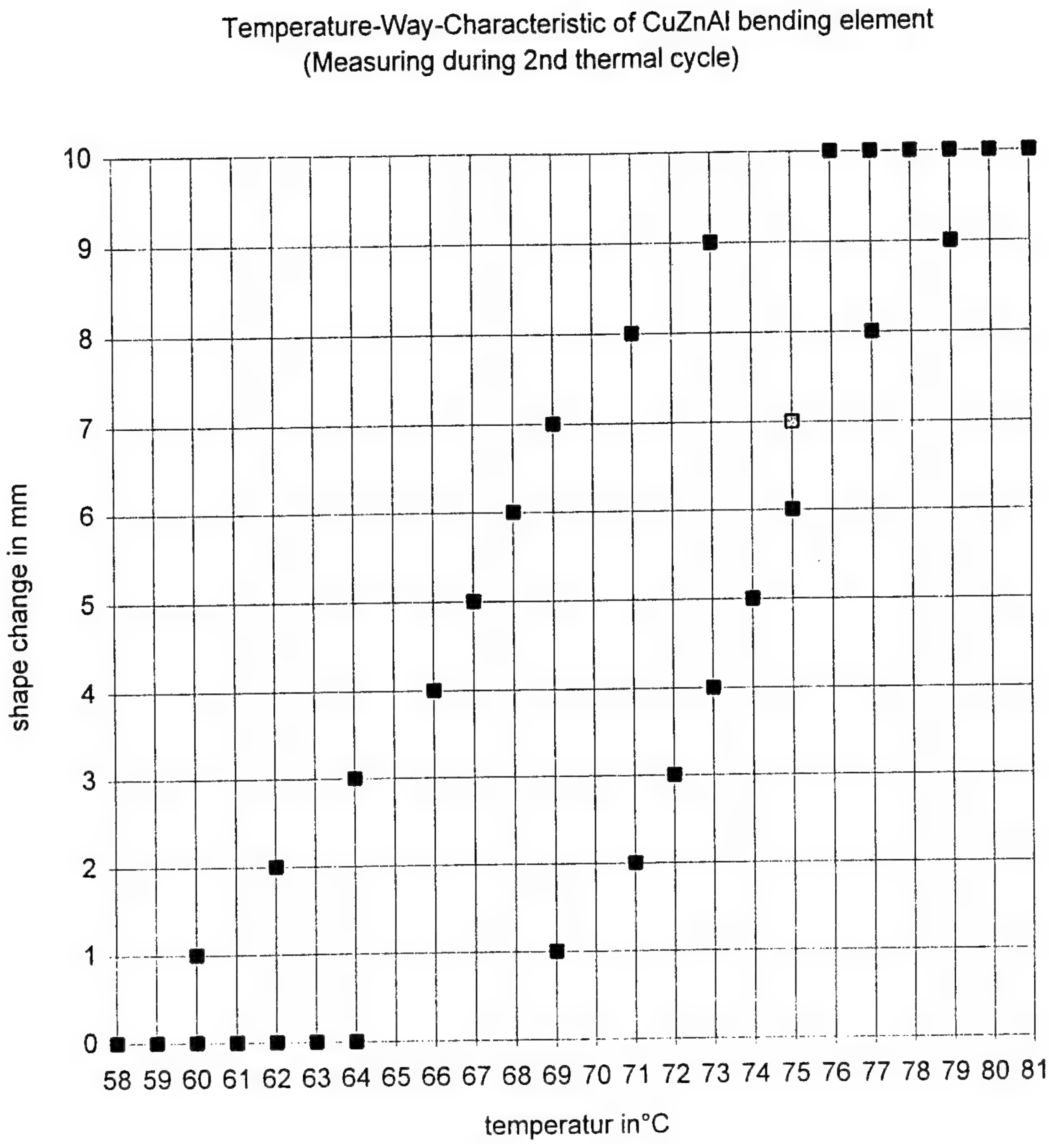
Temperature-Way-Characteristic of CuZnAl bending element
(Measuring during 2nd thermal cycle)
shape change in mm
0
1
2
3
4
5
6
7
8
9
10
58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81
temperatur in°C

Fig. 3.c.4

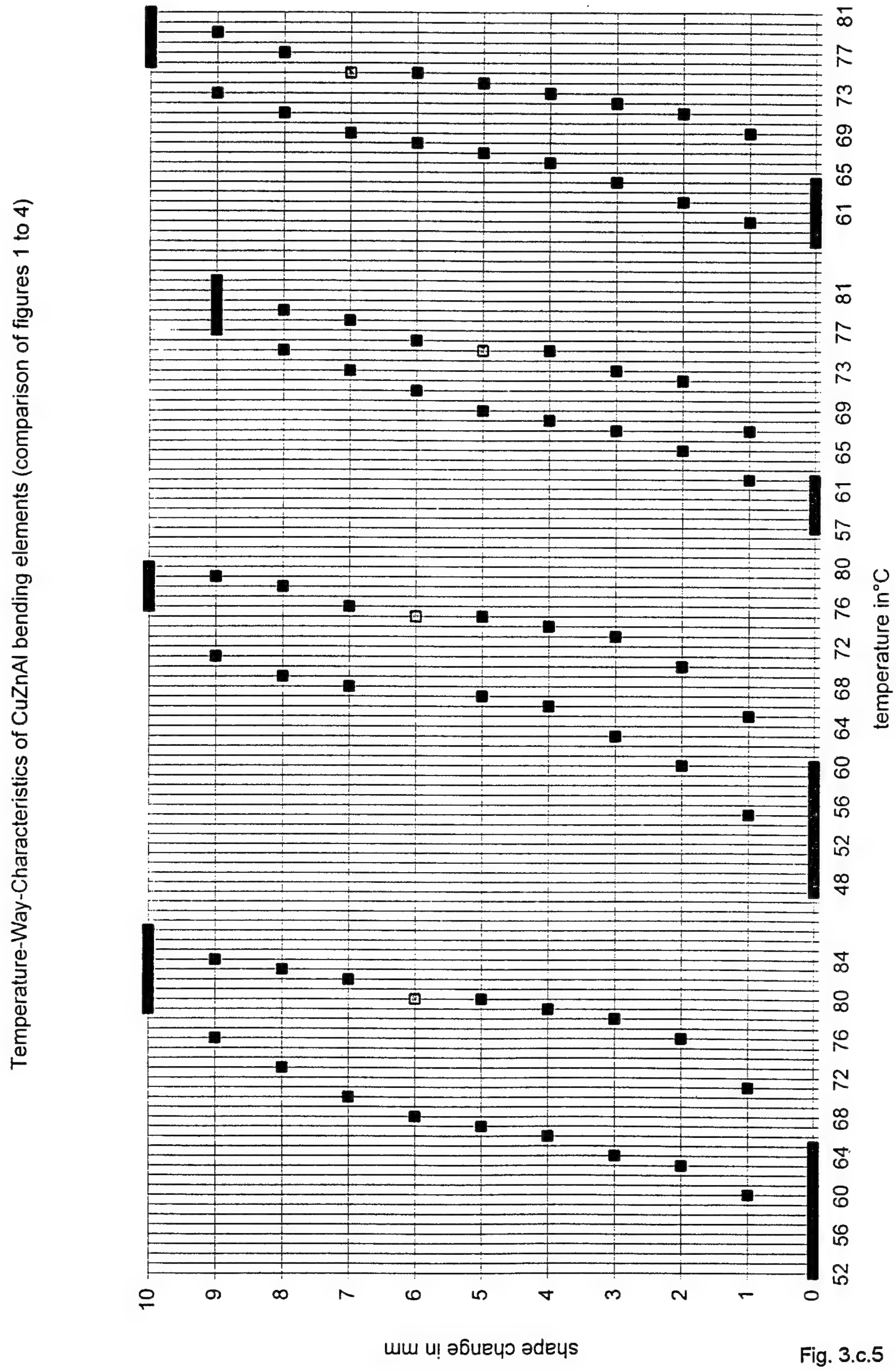
Temperature-Way-Characteristics of CuZnAl bending elements (comparison of figures 1 to 4)
temperature in°C
shape change in mm
10
9
8
7
6
5
4
3
2
1
0
52 56 60 64 68 72 76 80 84
48 52 56 60 64 68 72 76 80
57 61 65 69 73 77 81
61 65 69 73 77 81

Fig. 3.c.5

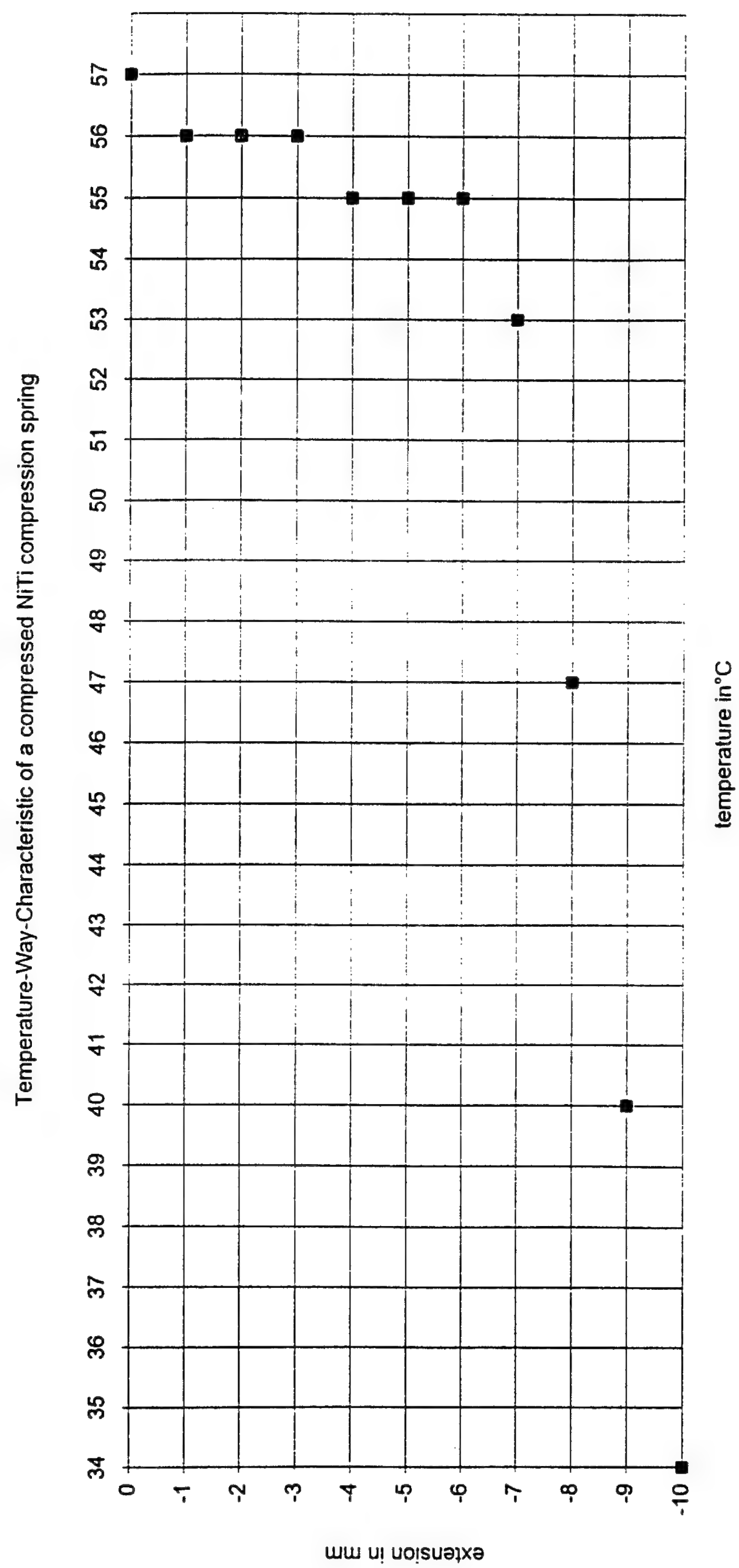
Temperature-Way-Characteristic of a compressed NiTi compression spring
temperature in°C
extension in mm
57
56
55
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
34
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10

Fig. 3.c.6

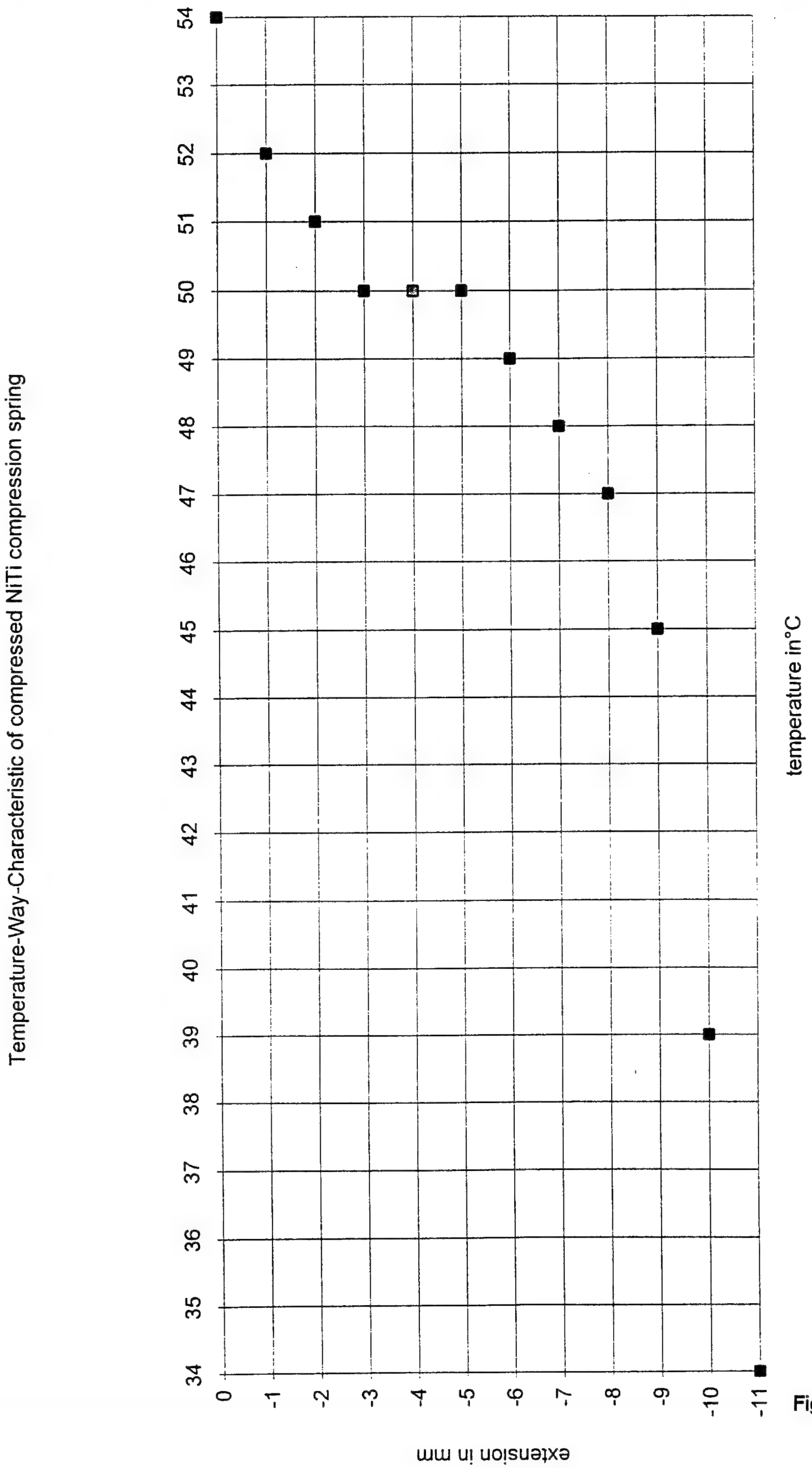
Temperature-Way-Characteristic of compressed NiTi compression spring
temperature in°C
extension in mm
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
34
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11

Fig. 3.c.7

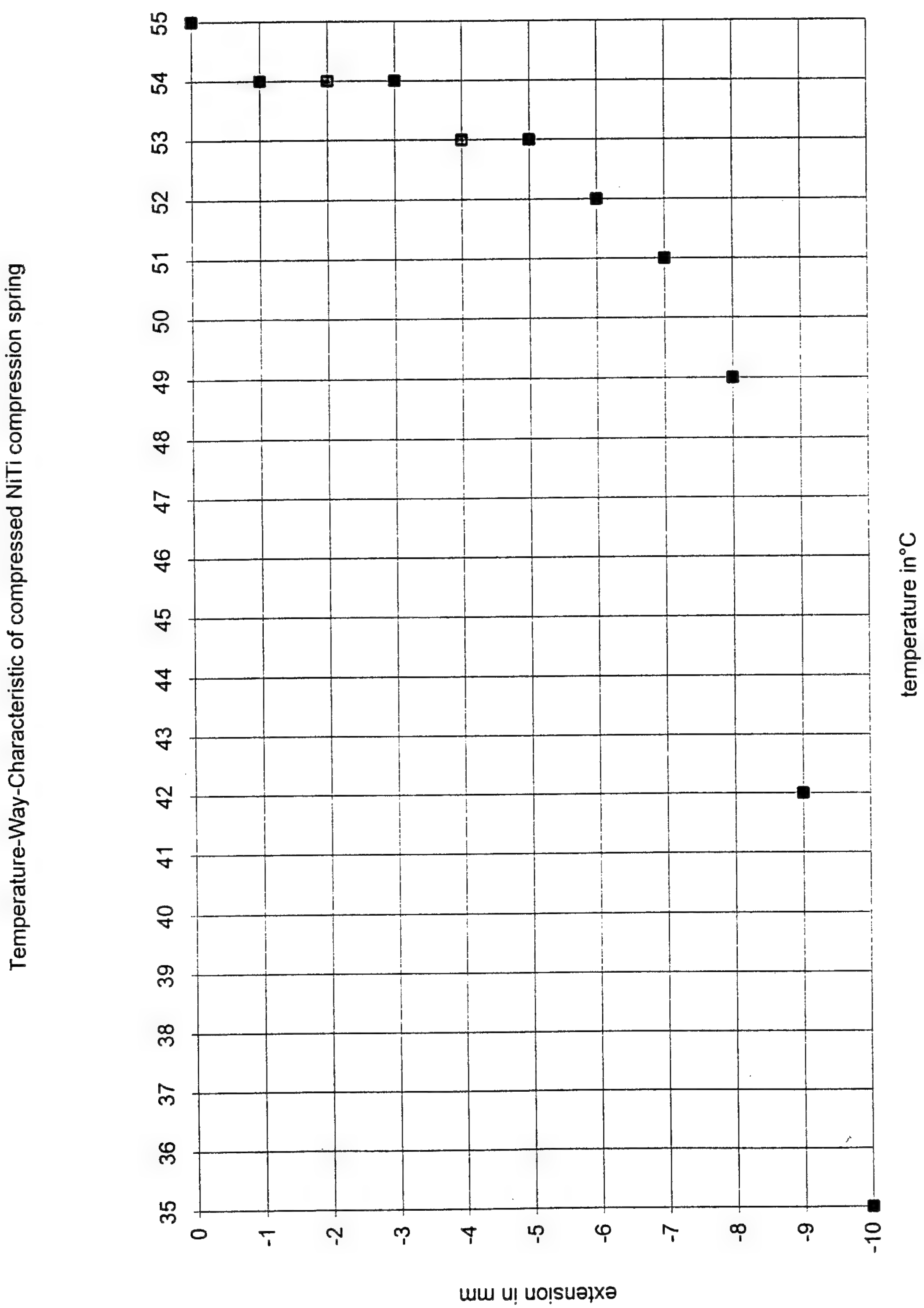
Temperature-Way-Characteristic of compressed NiTi compression spring
temperature in°C
extension in mm
55
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10

Fig. 3.c.8

Temperature-Way-Characteristic of compressed NiTi compression spring

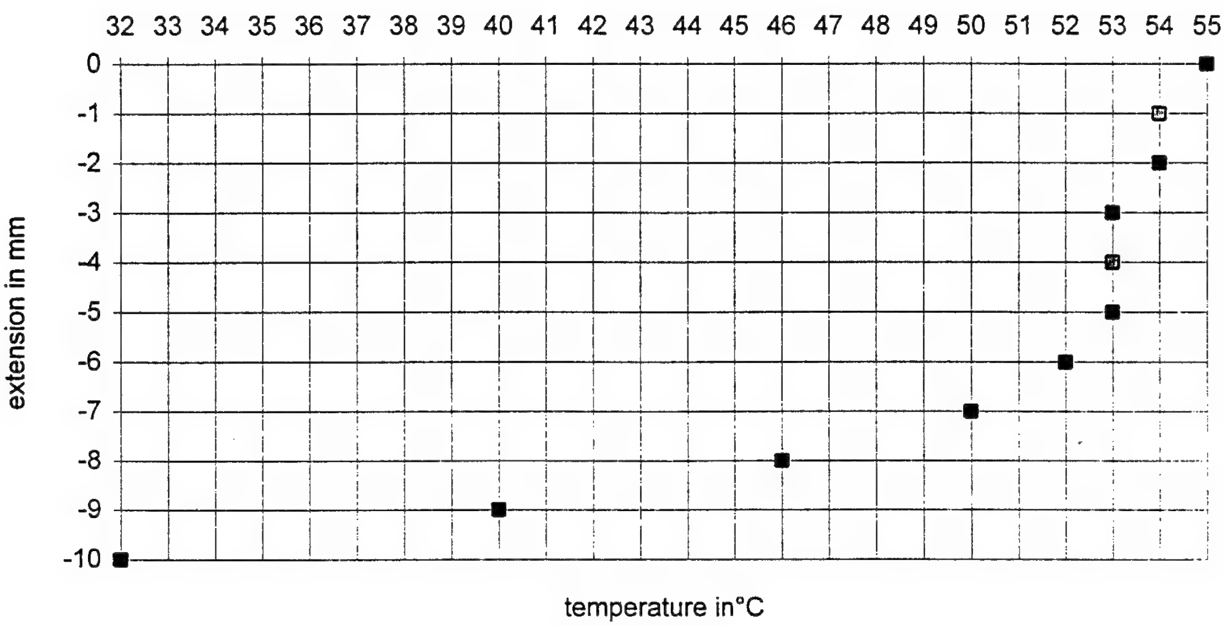

Fig. 3.c.9

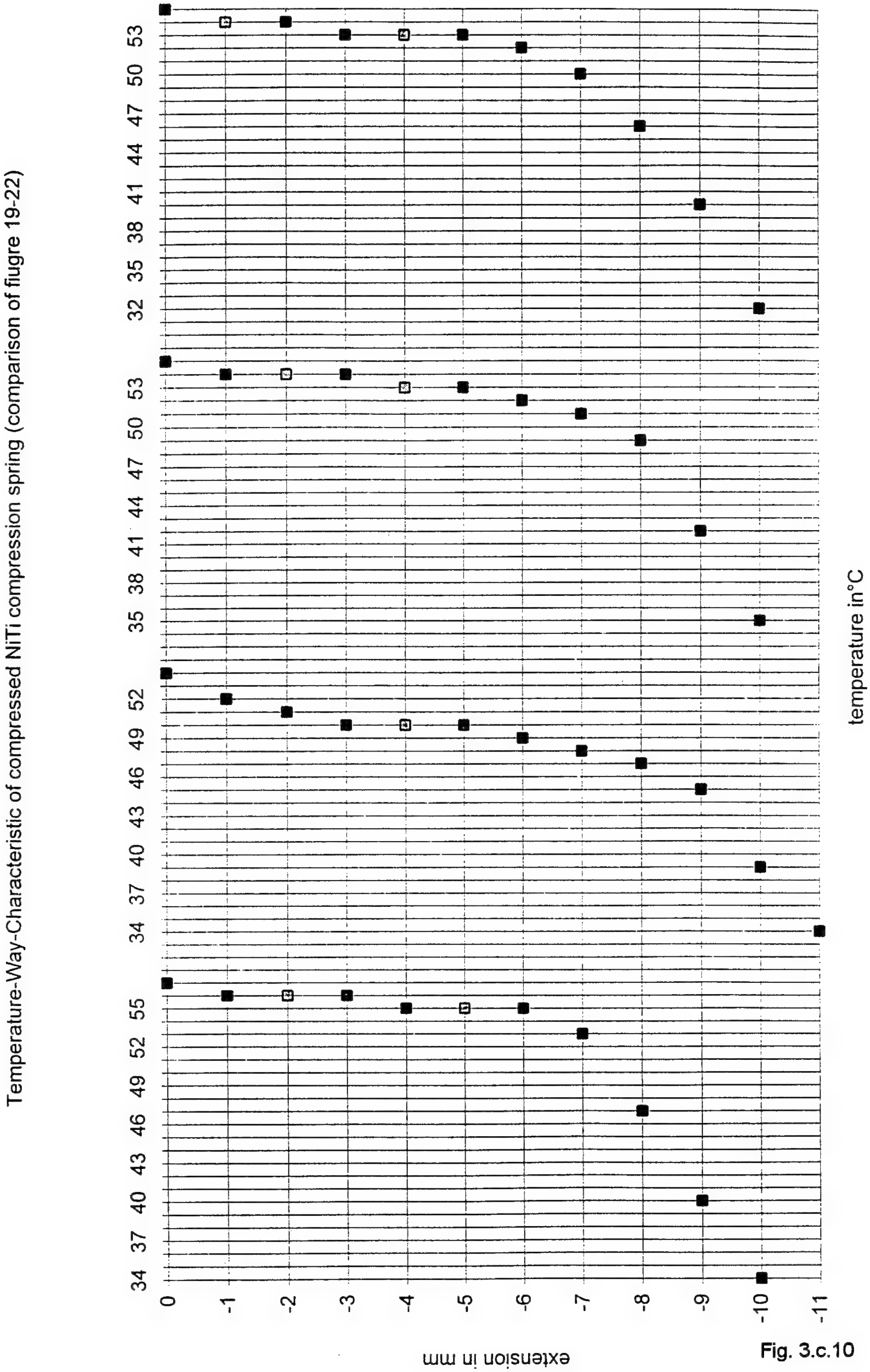
Temperature-Way-Characteristic of compressed NiTi compression spring (comparison of fiugre 19-22)
temperature in°C
extension in mm

Fig. 3.c.10

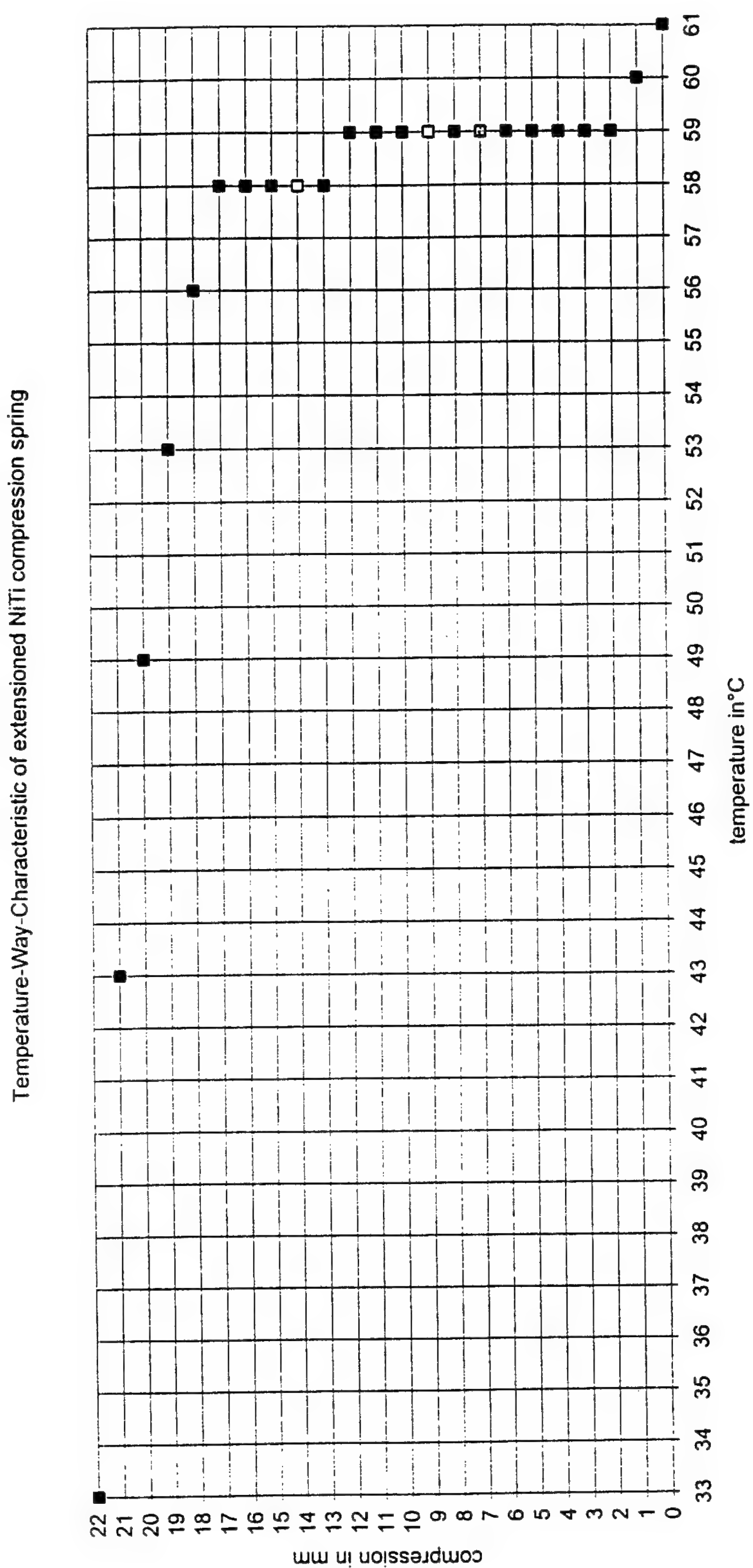
Temperature-Way-Characteristic of extensioned NiTi compression spring
temperature in°C
compression in mm

Fig. 3.c.11

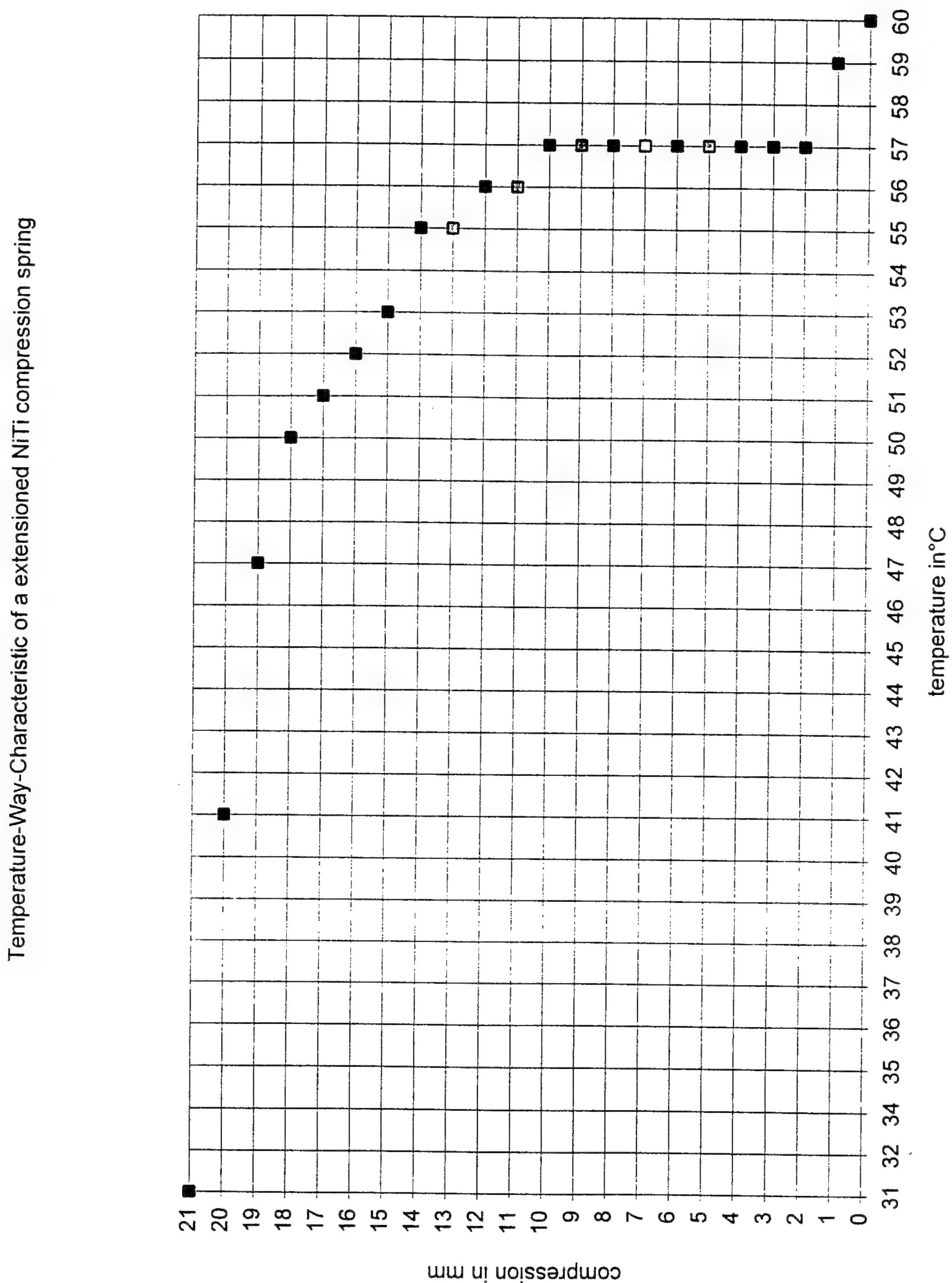
Temperature-Way-Characteristic of a extensioned NiTi compression spring
temperature in°C
compression in mm

Fig. 3.c.12

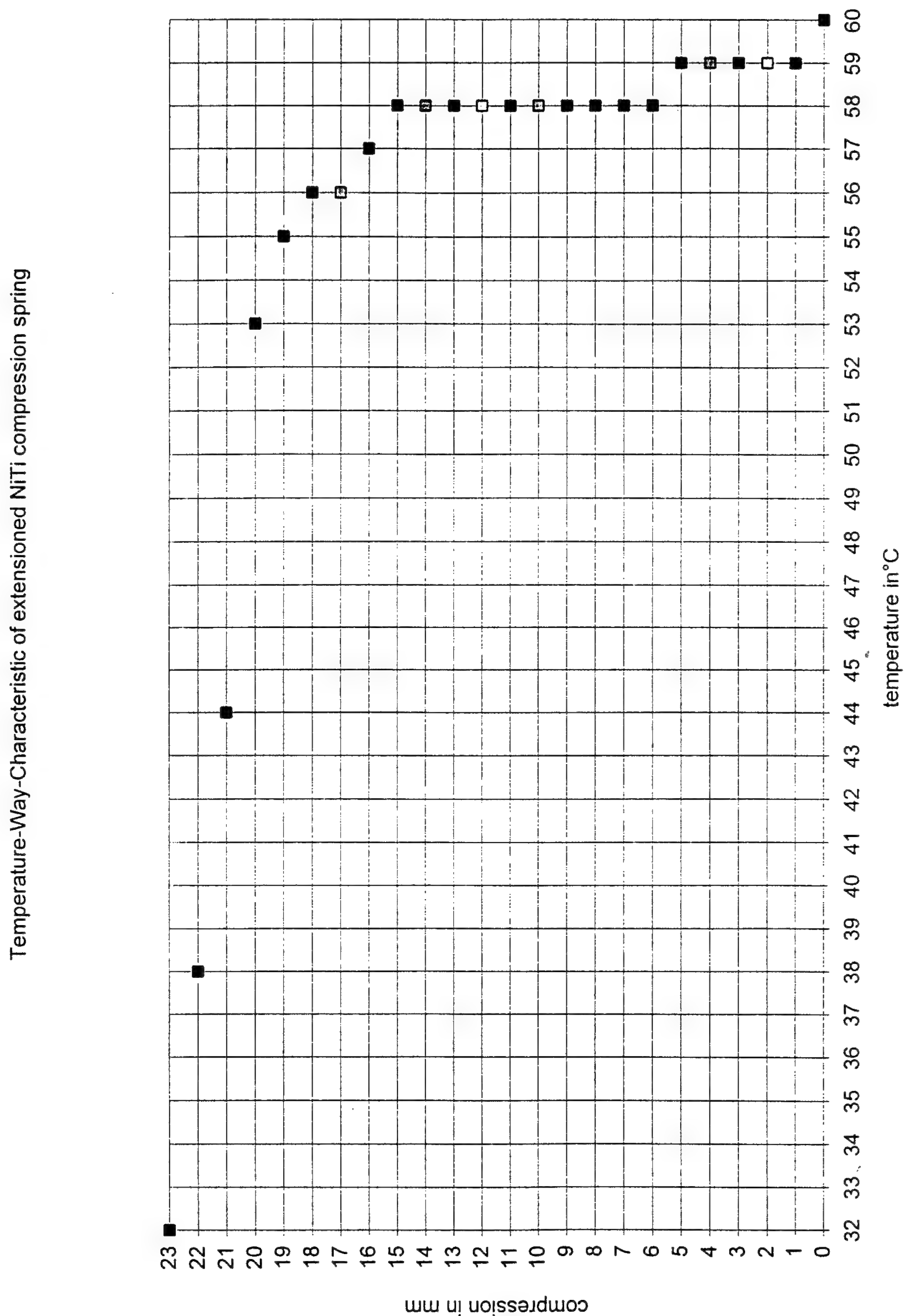
Temperature-Way-Characteristic of extensioned NiTi compression spring
temperature in°C
compression in mm

Fig. 3.c.13

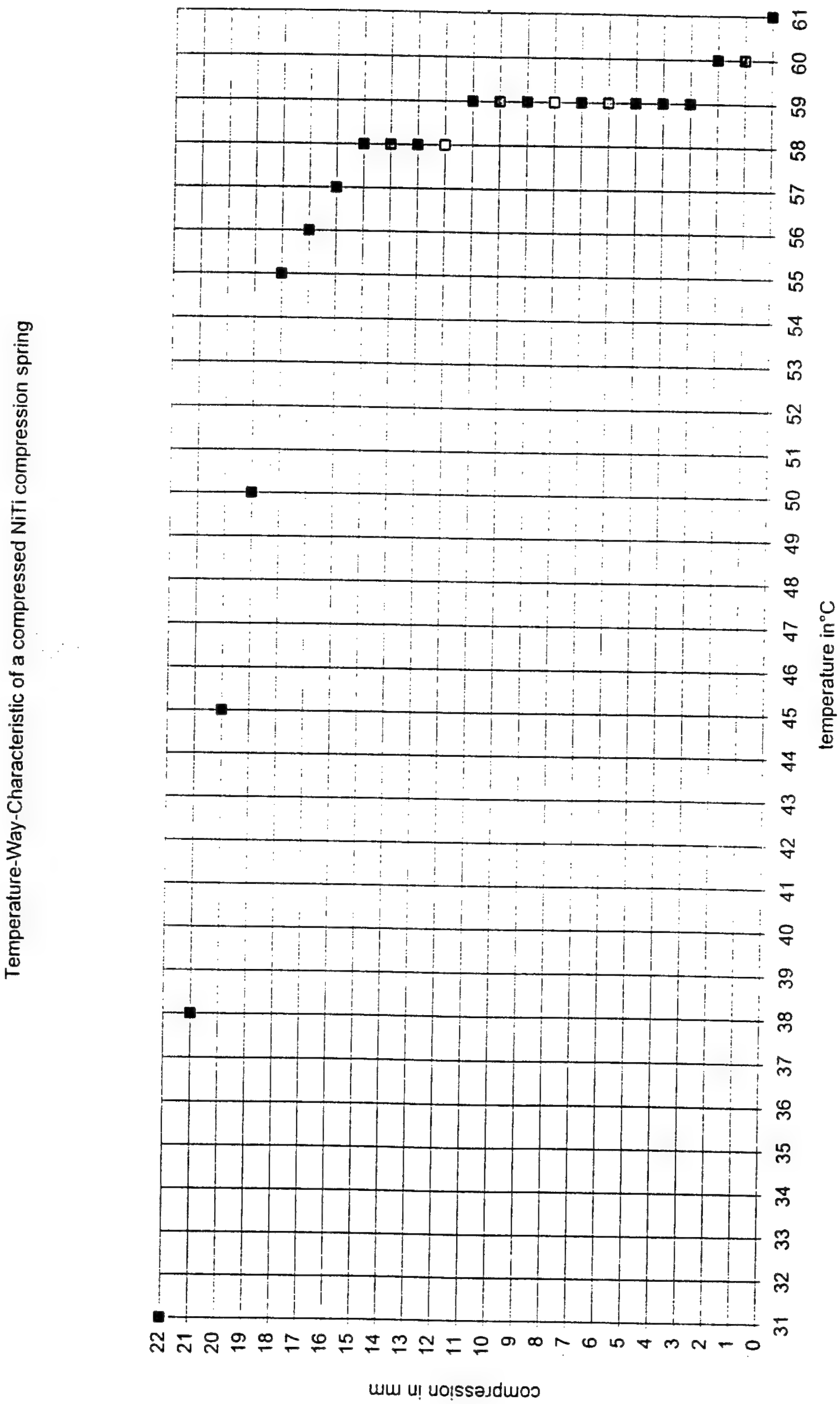
Temperature-Way-Characteristic of a compressed NiTi compression spring
temperature in°C
compression in mm

Fig. 3.c.14

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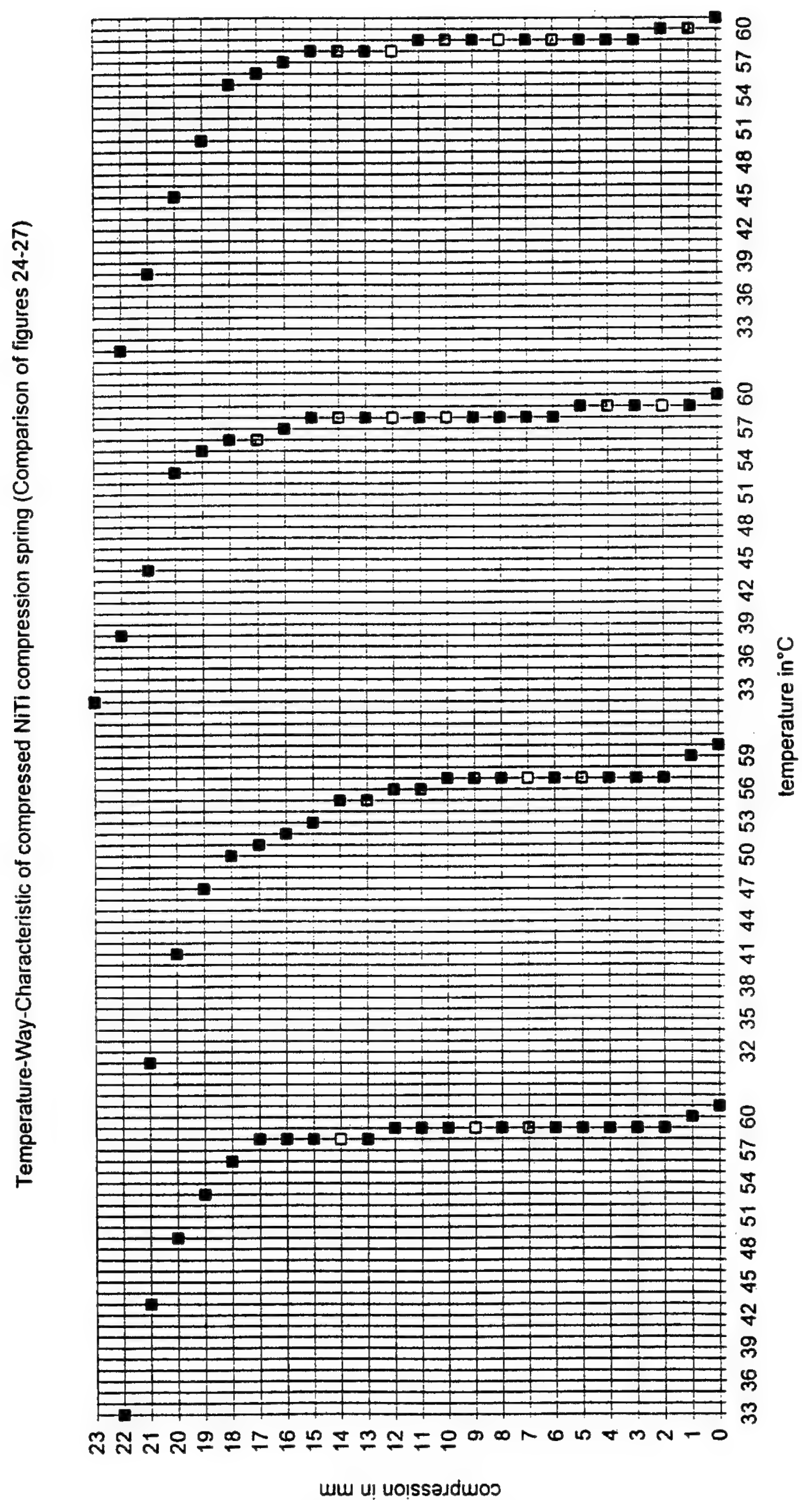

Fig. 3.c.15

Temperature-Way-Characteristic of NiTi compression spring - material is trained for a two-way shape memory (after 1st training)

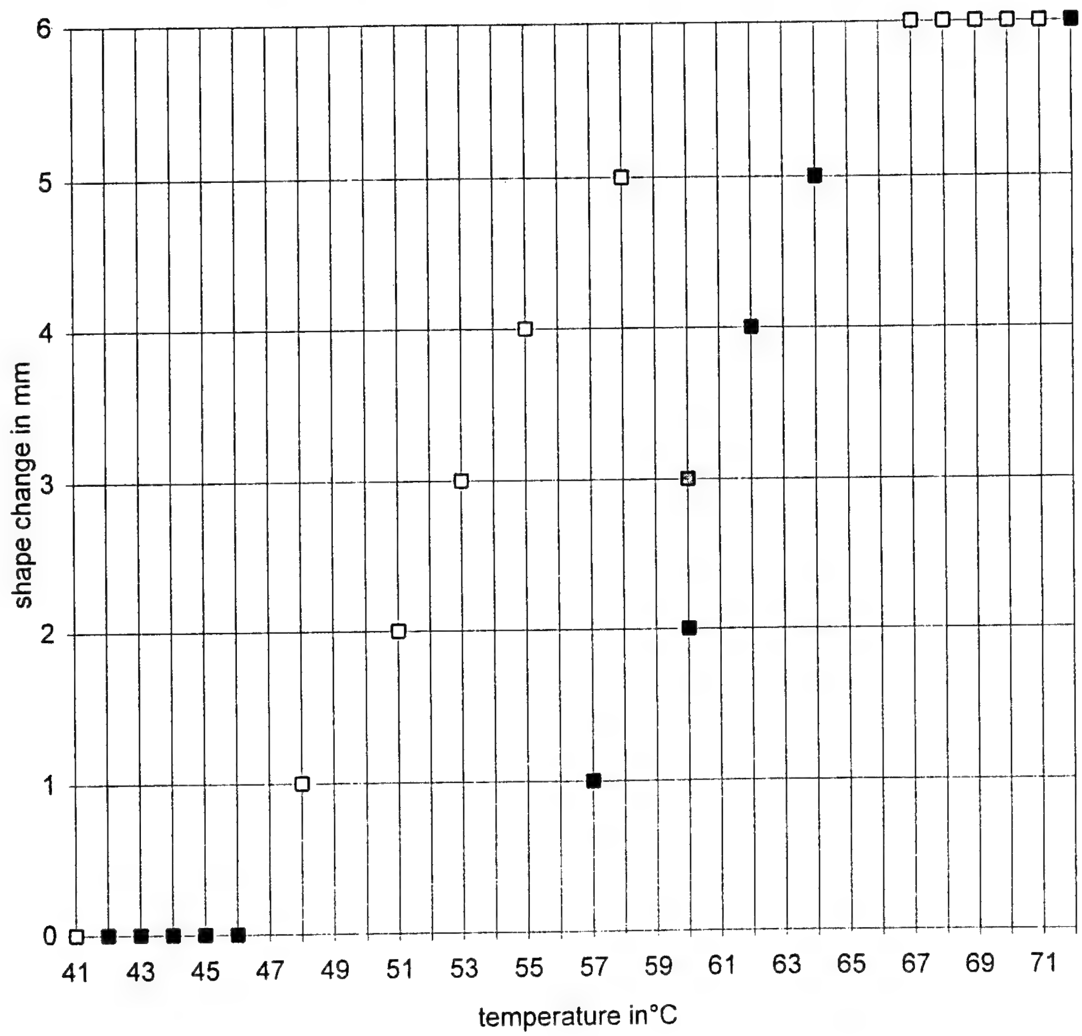

Fig. 3.c.16

DAUM®

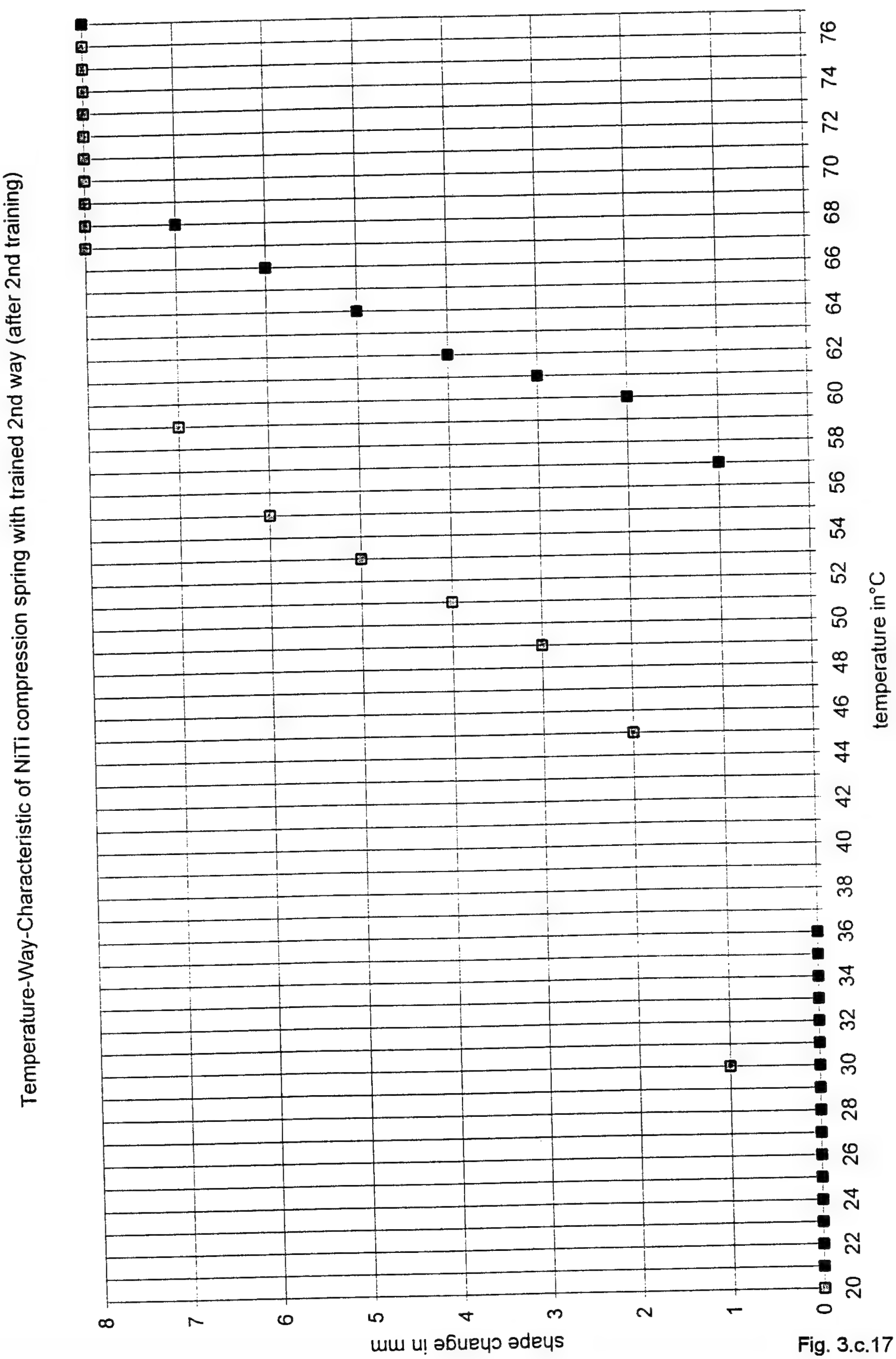

Fig. 3.c.17

DAUM®

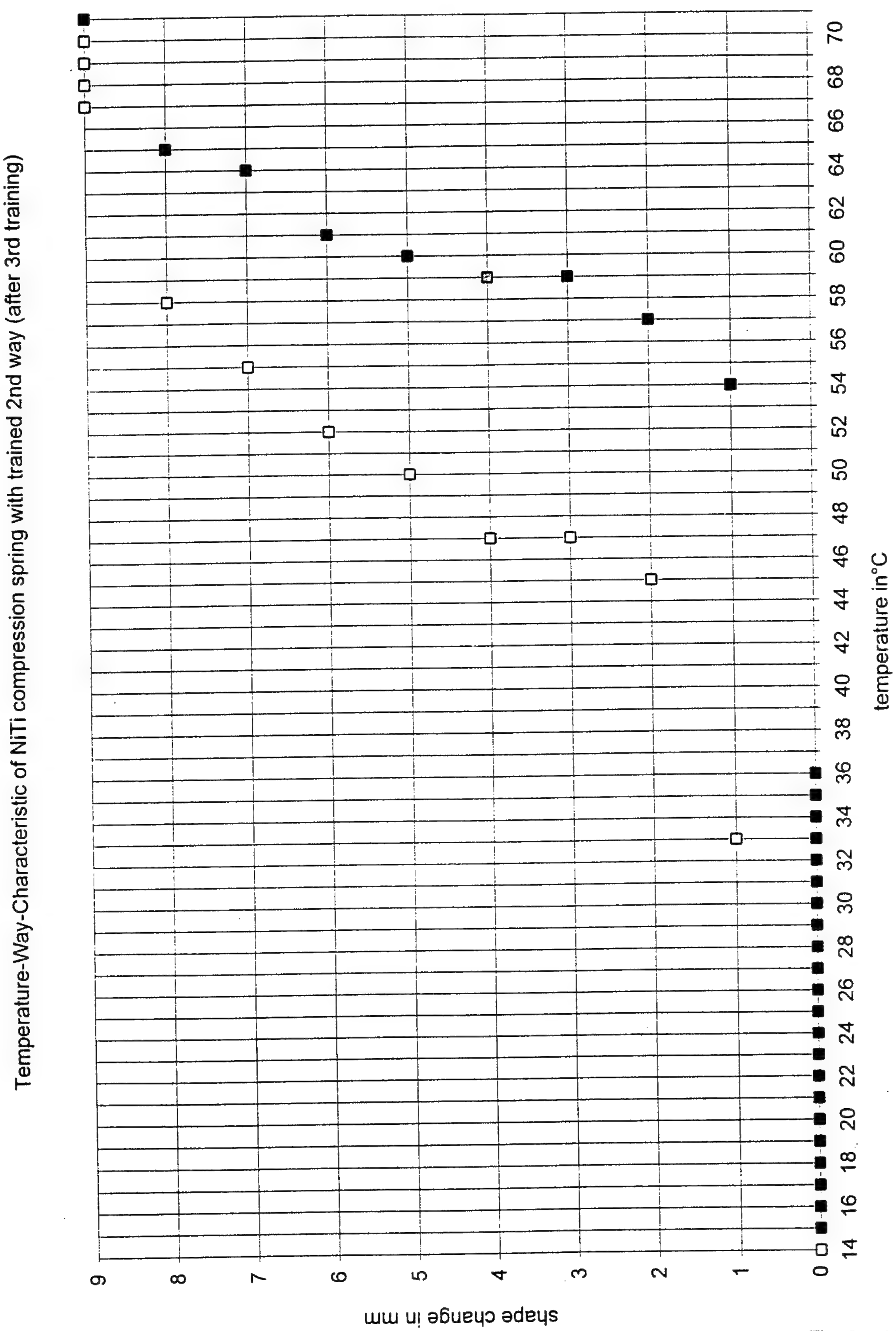

Fig. 3.c.18

DAUM®

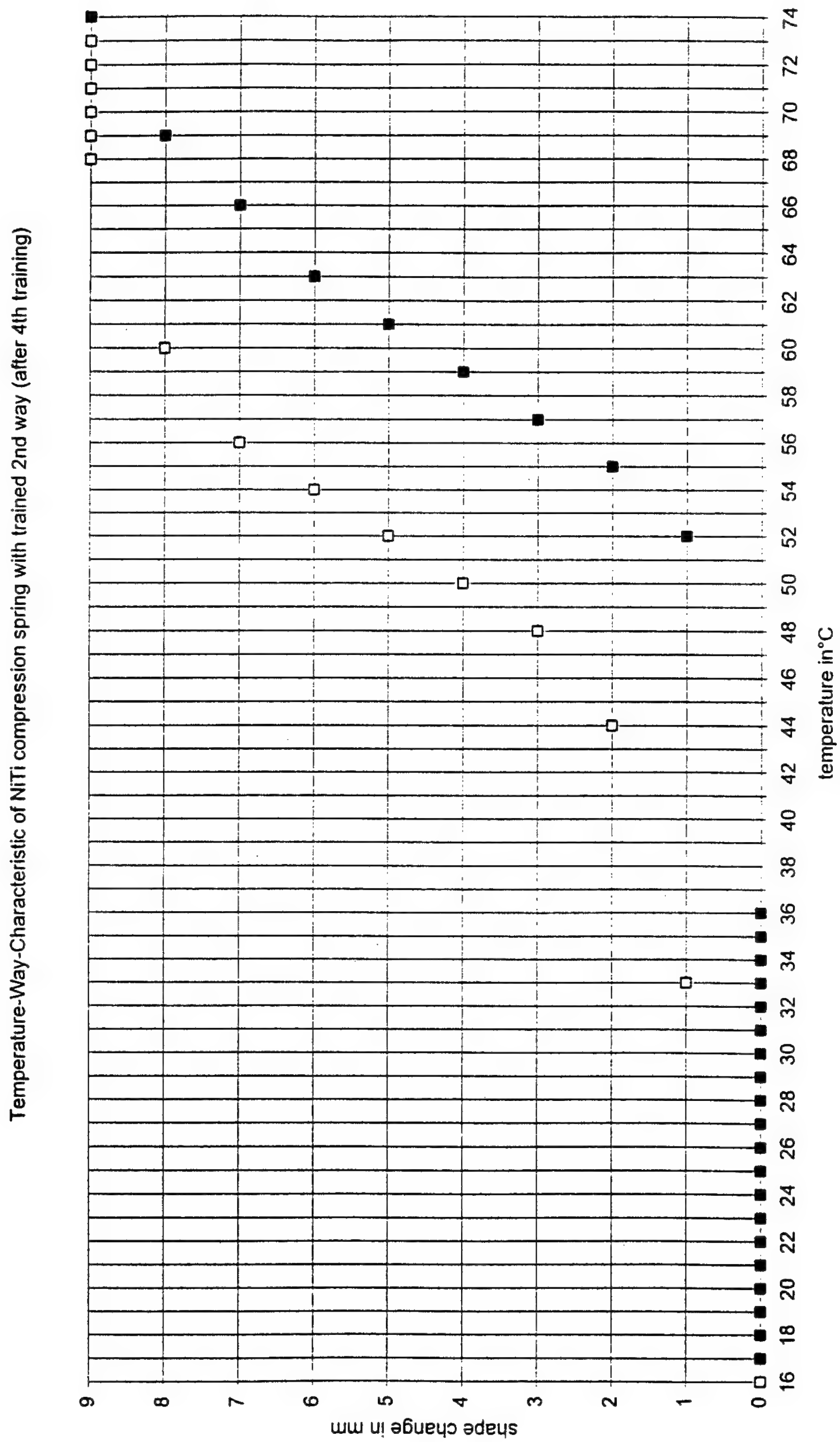

Fig. 3.c.19

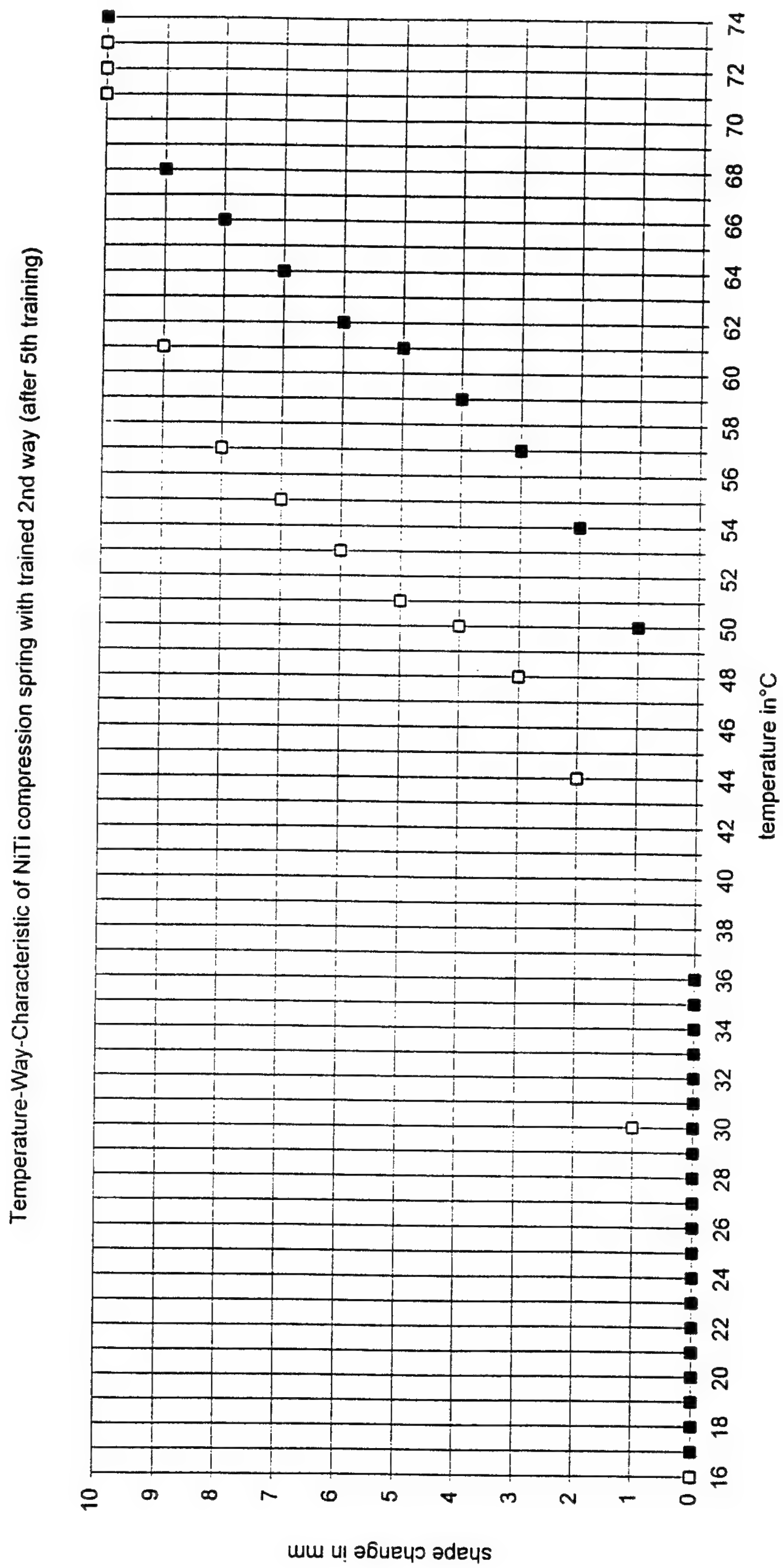
Temperature-Way-Characteristic of NiTi compression spring with trained 2nd way (after 5th training)
temperature in°C
shape change in mm
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
70
72
74
0
1
2
3
4
5
6
7
8
9
10

Fig. 3.c.20

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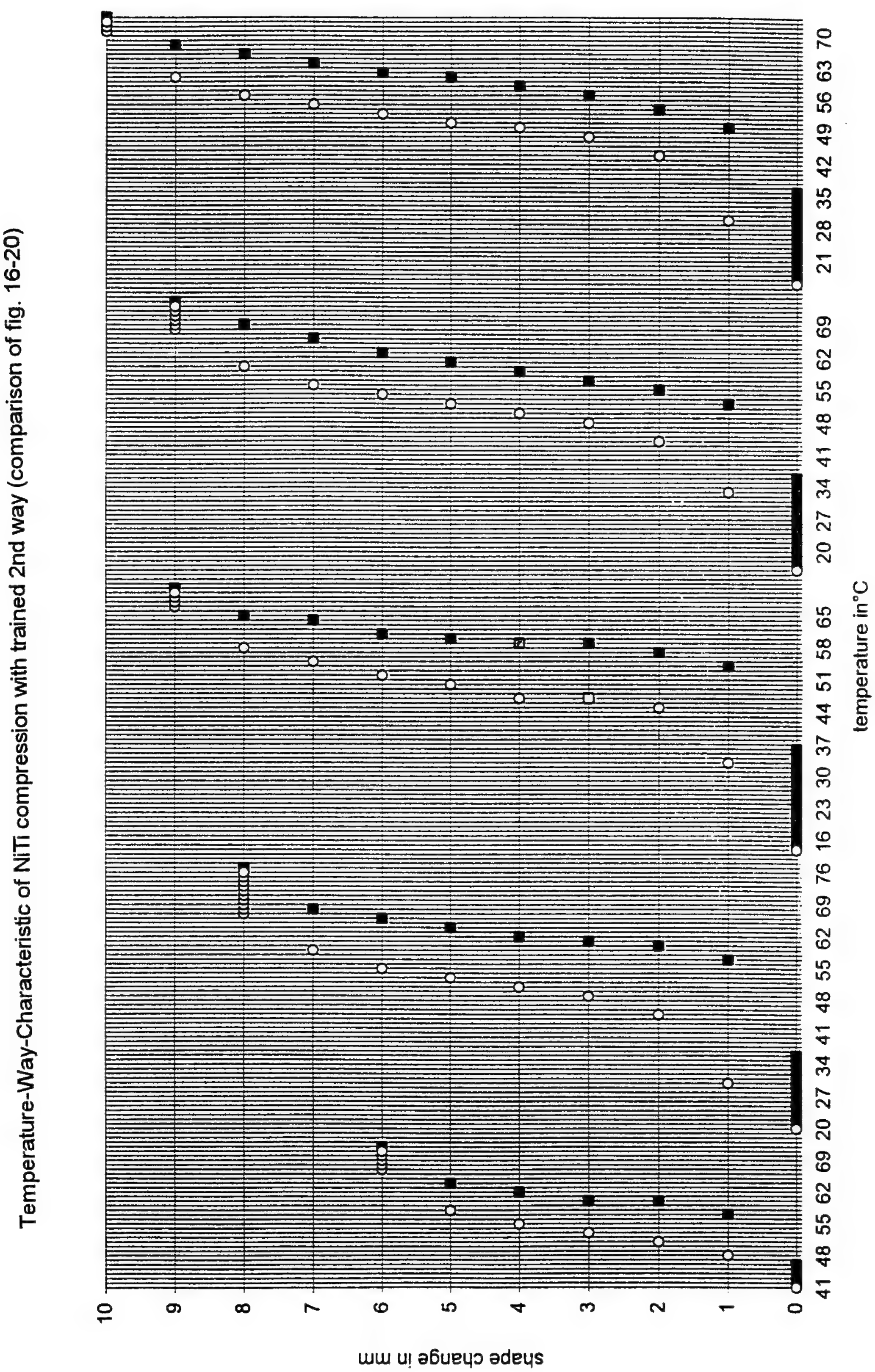


Fig. 3.c.21

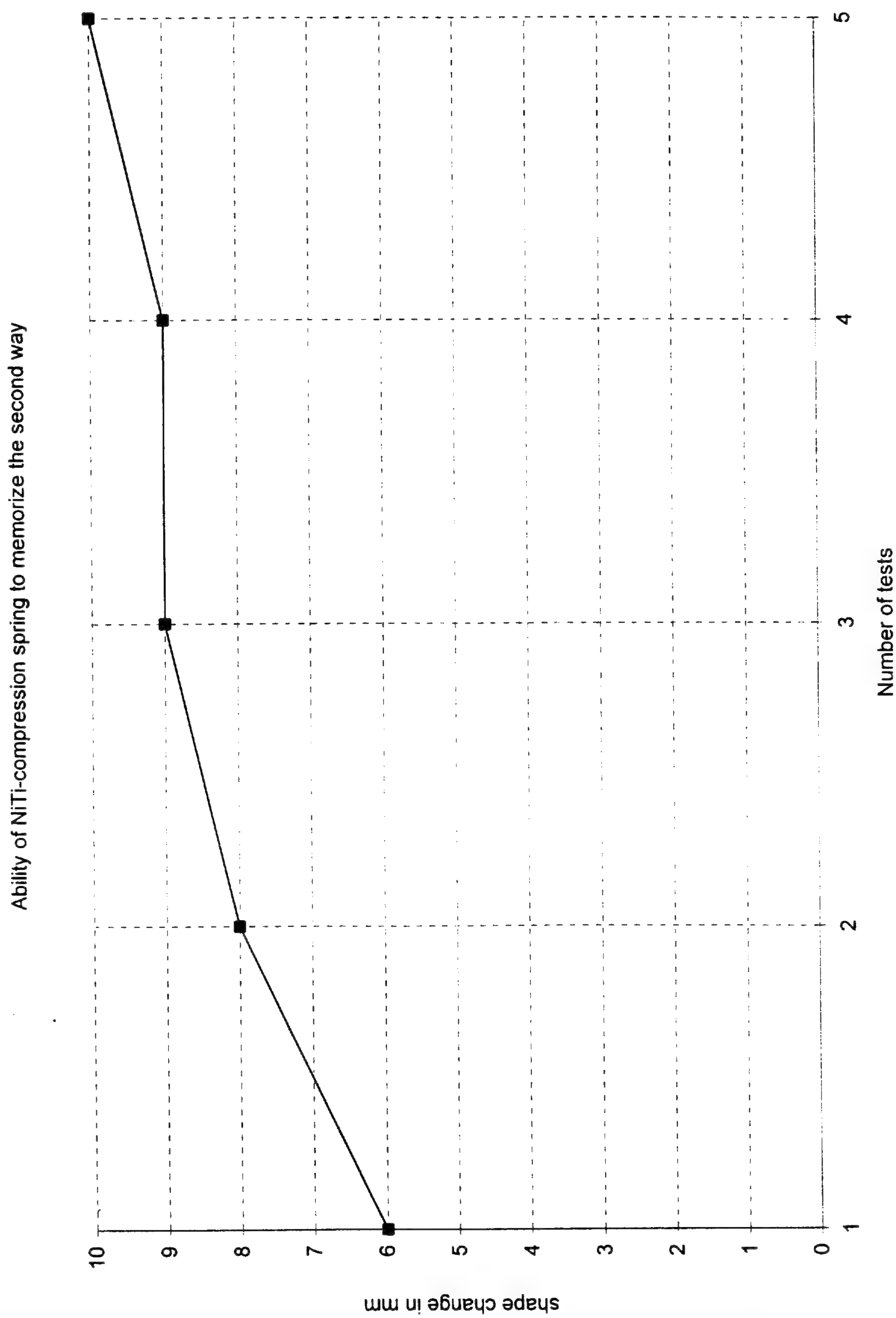

Ability of NiTi-compression spring to memorize the second way
shape change in mm
10
9
8
7
6
5
4
3
2
1
0
Number of tests
1
2
3
4
5

Fig. 3.c.2
2

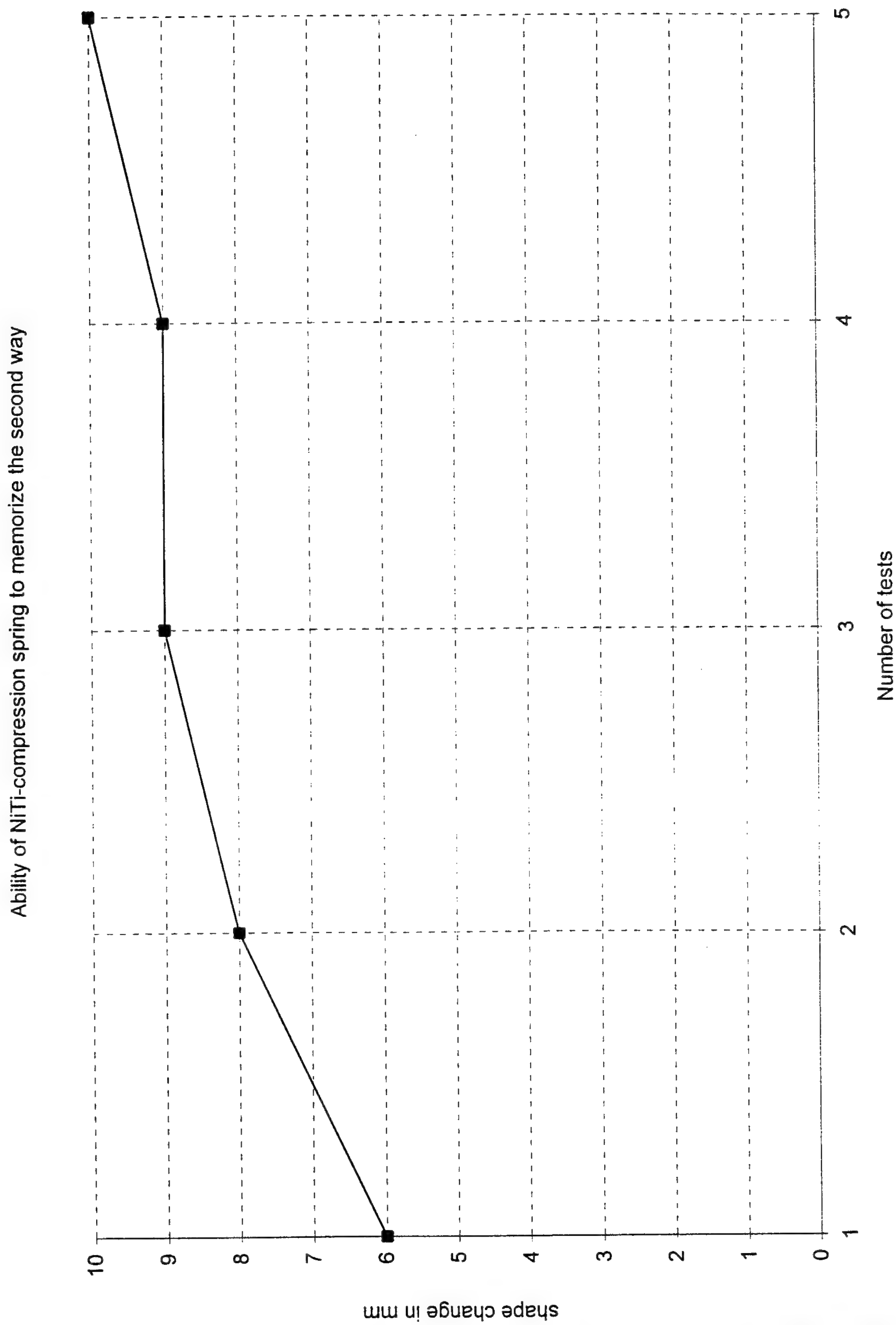

Ability of NiTi-compression spring to memorize the second way
shape change in mm
0
1
2
3
4
5
6
7
8
9
10
Number of tests
1
2
3
4
5

Fig. 3.c.23

Fig. 3.c.23a

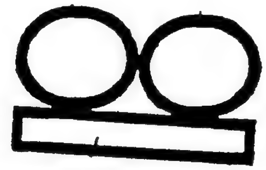


Fig. 3.c.23b

Fig. 3.c.23c

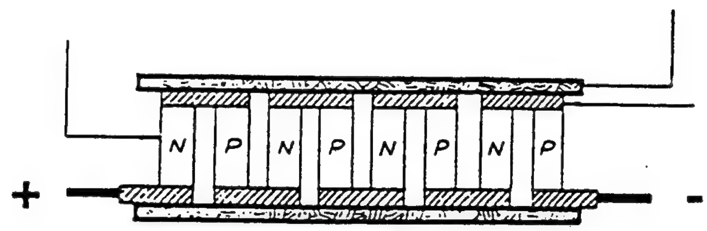


Fig. 3.c.23d

Fig. 3.c.23e

construction of finger

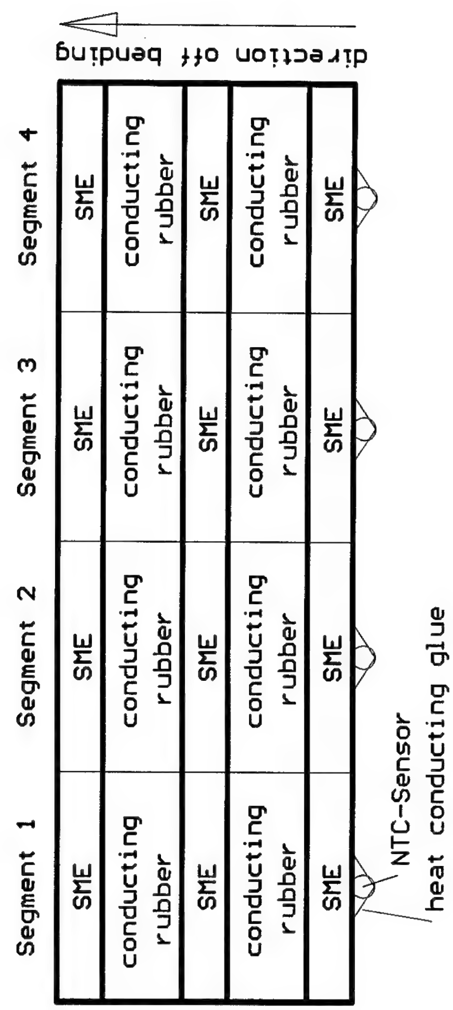


Fig. 3.c.24

principle of controling unit

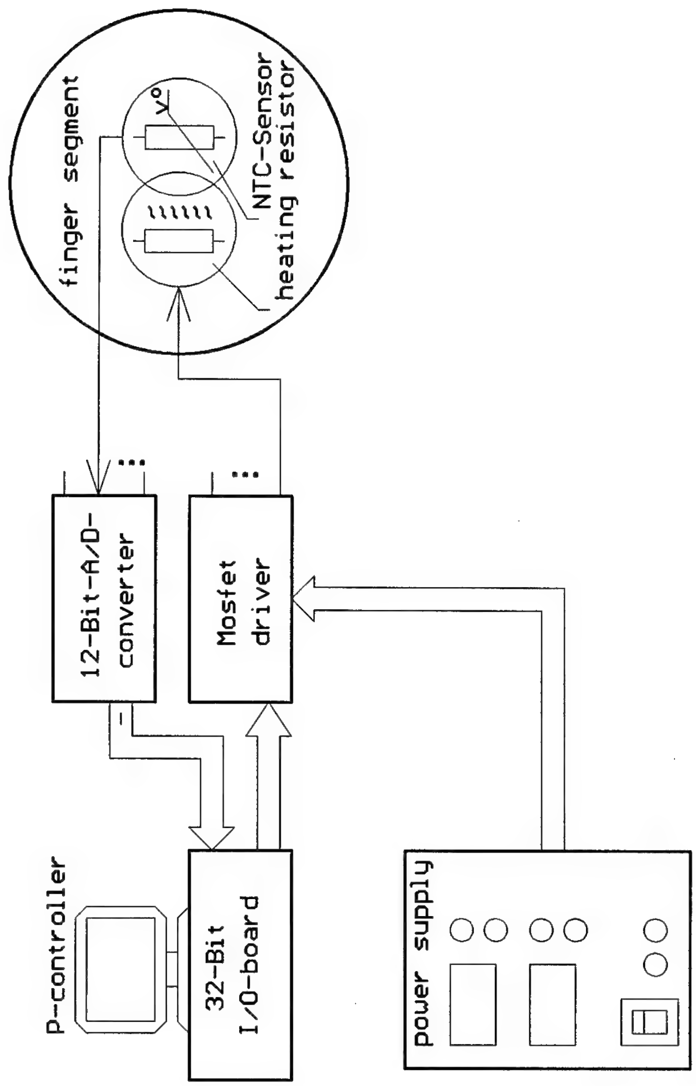
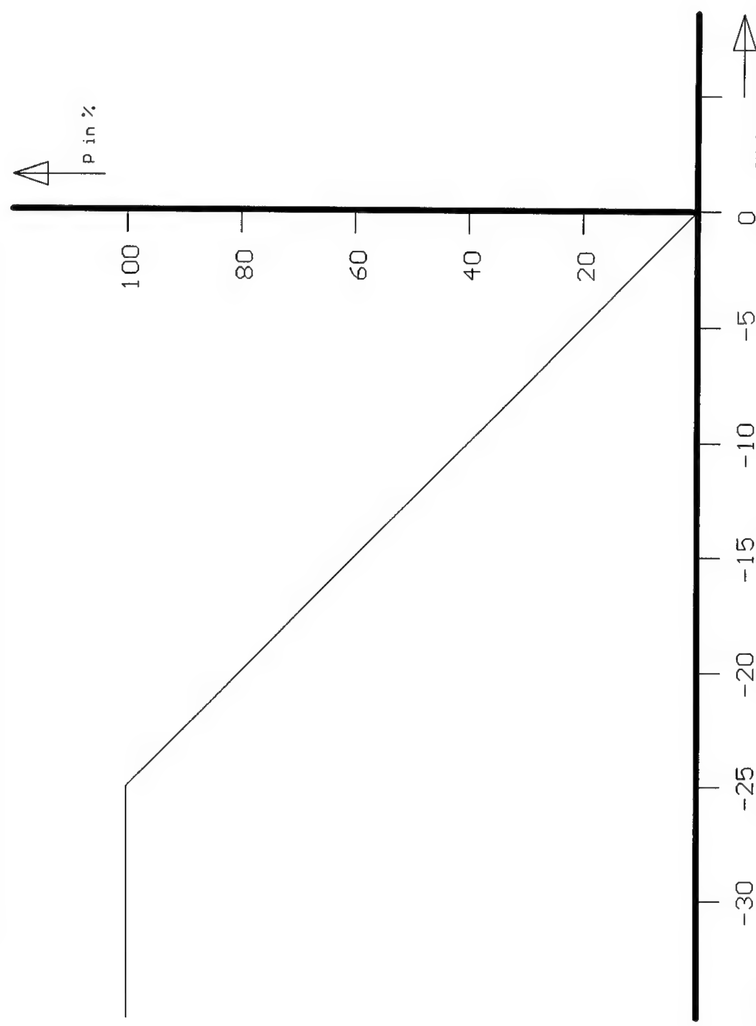


Fig. 3.c.25



pulsuide as function of temperature difference

Fig. 3.c.25

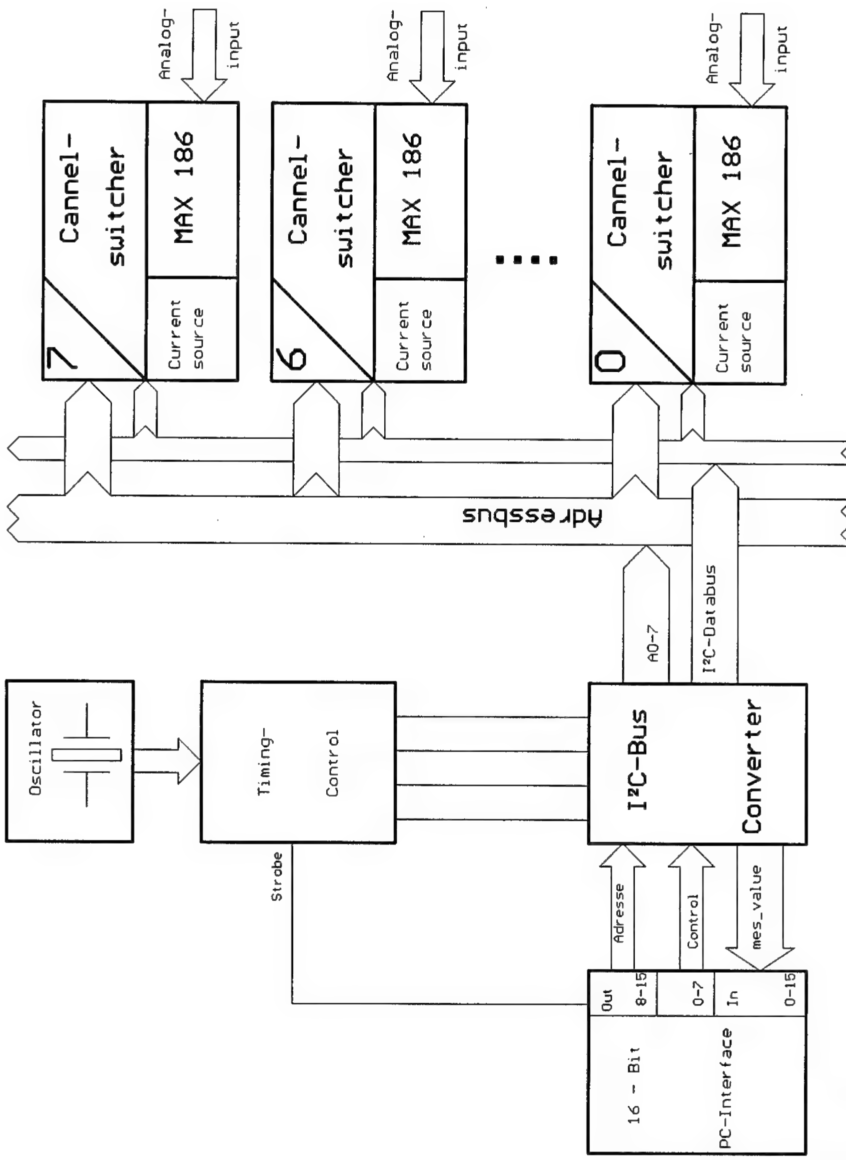

Analog-
input
Cannel-
switcher
MAX 186
Current
source
7
6
0
....
Adressbus
A0-7
I²C-Databus
Oscillator
Timing-
Control
I²C-Bus
Converter
Strobe
Adresse
Control
mes_value
Out
8-15
0-7
In
0-15
16 - Bit
PC-Interface

Fig. 3.c.27

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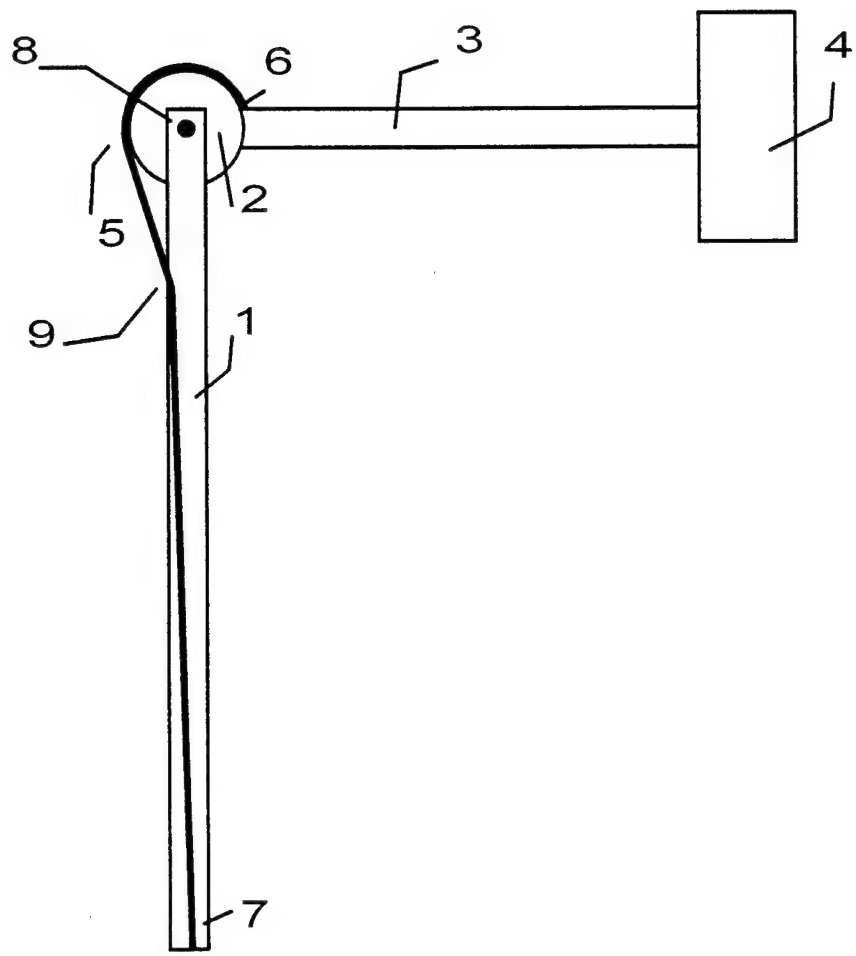

Fig. 3.c.28

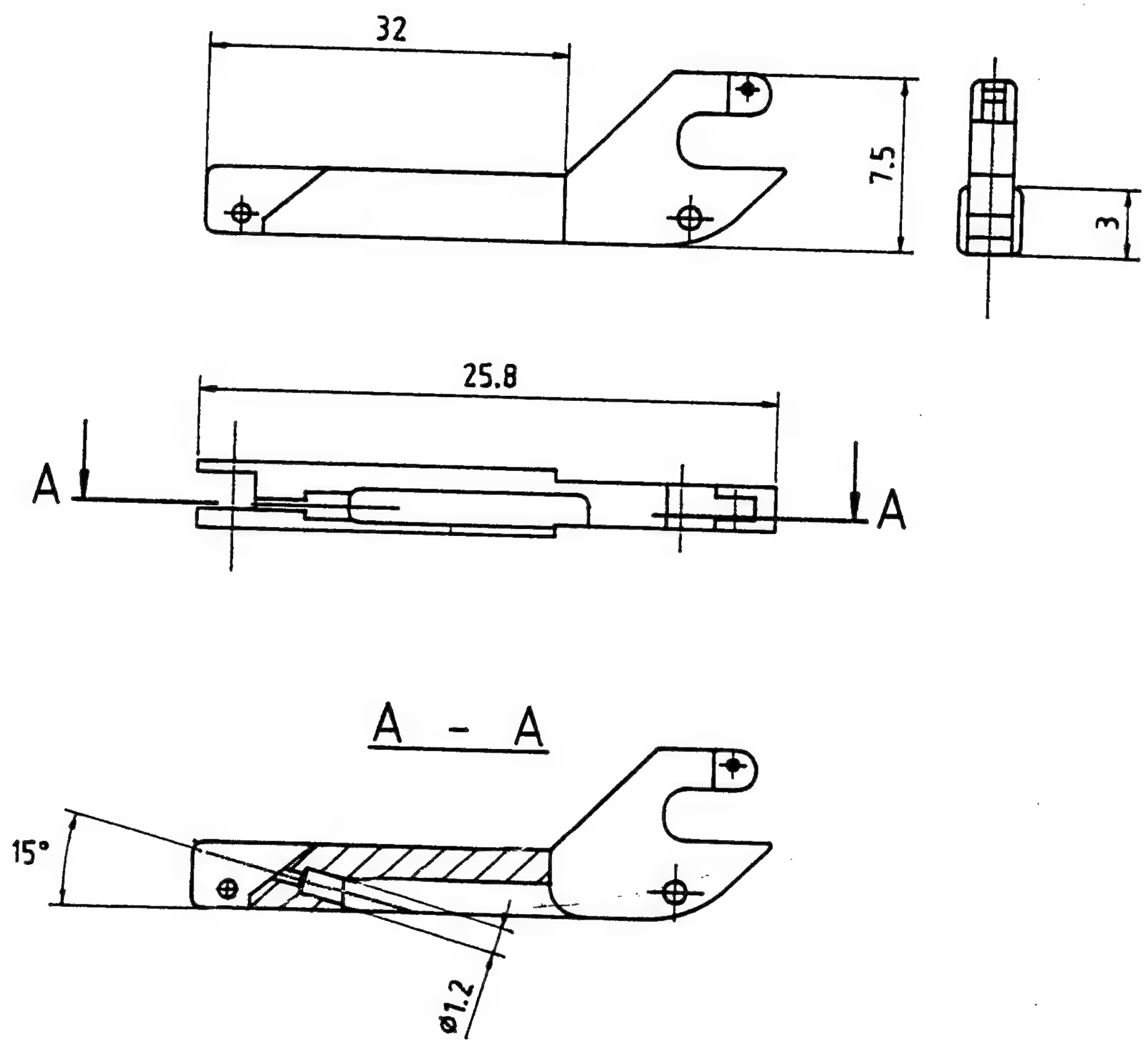

Fig. 3.c.29

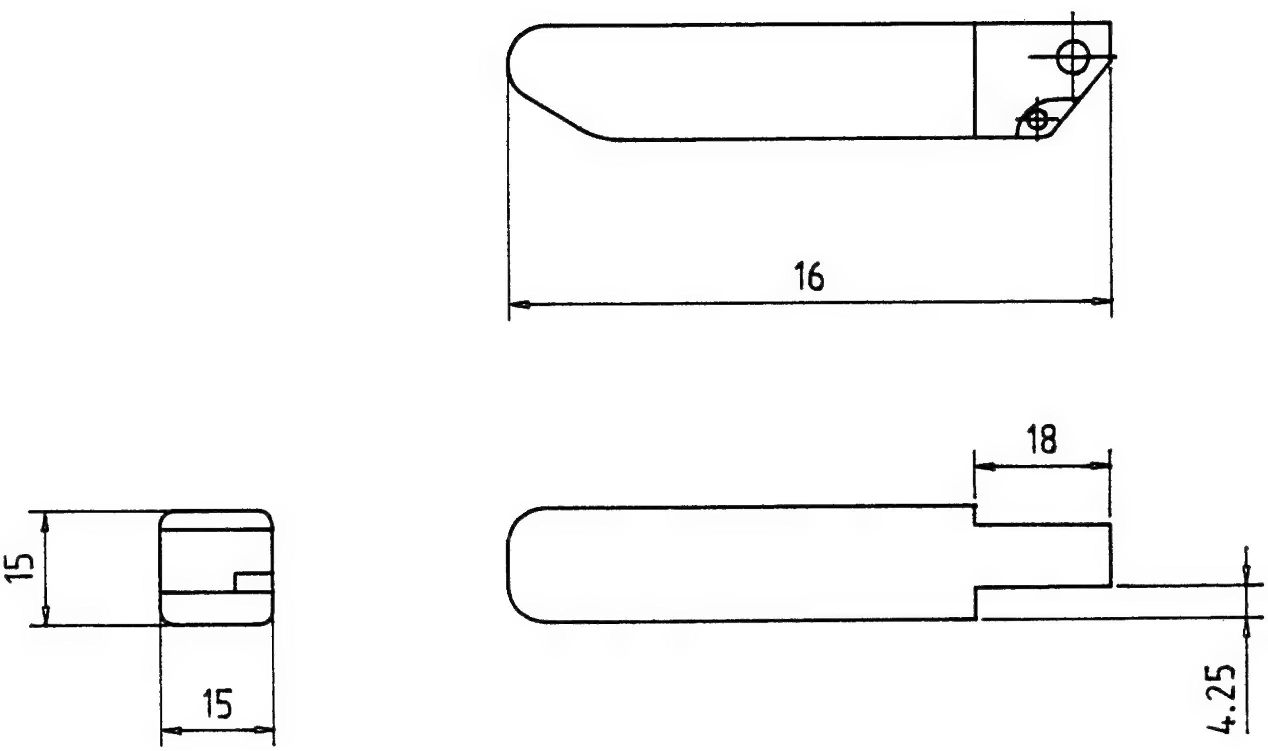

Fig. 3.c.30

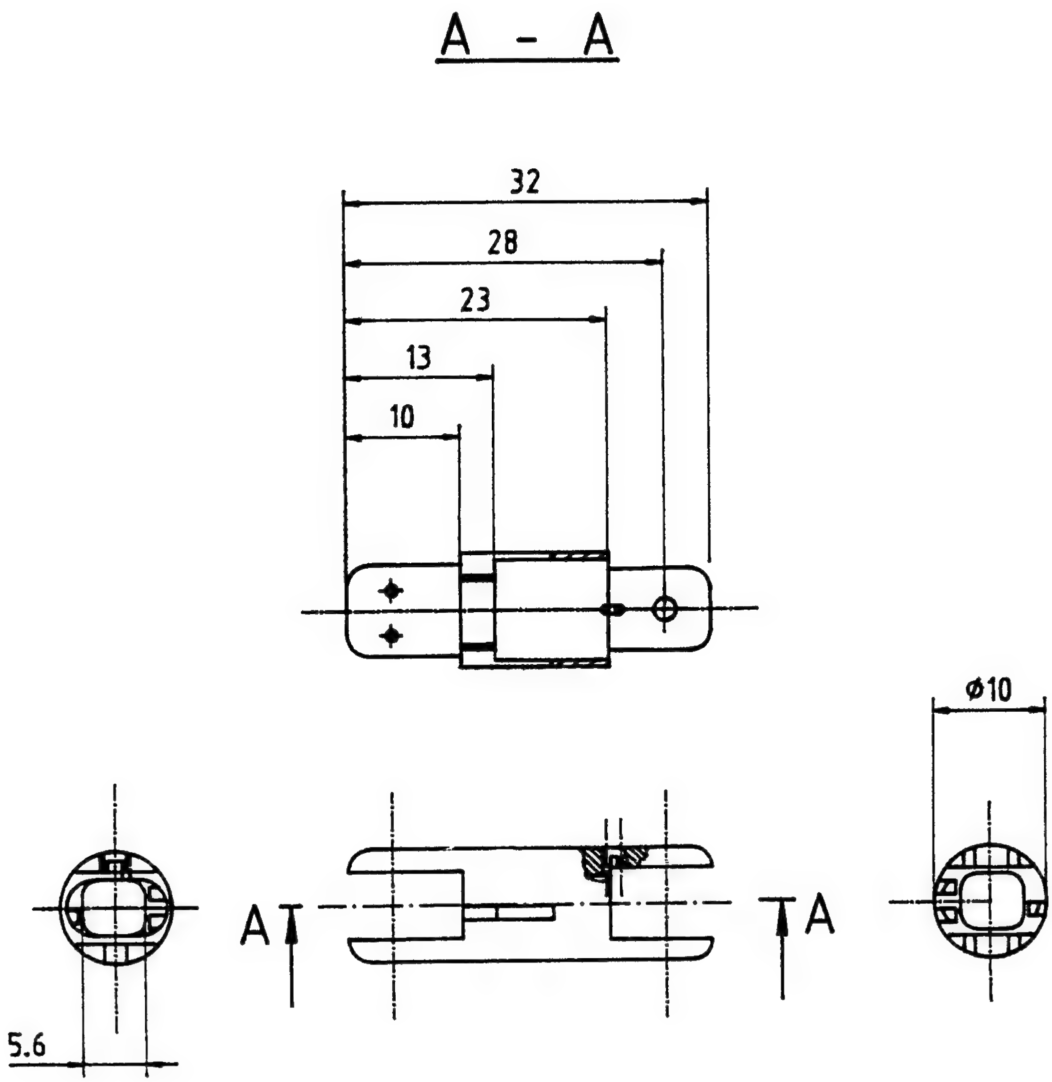

Fig. 3.c.31

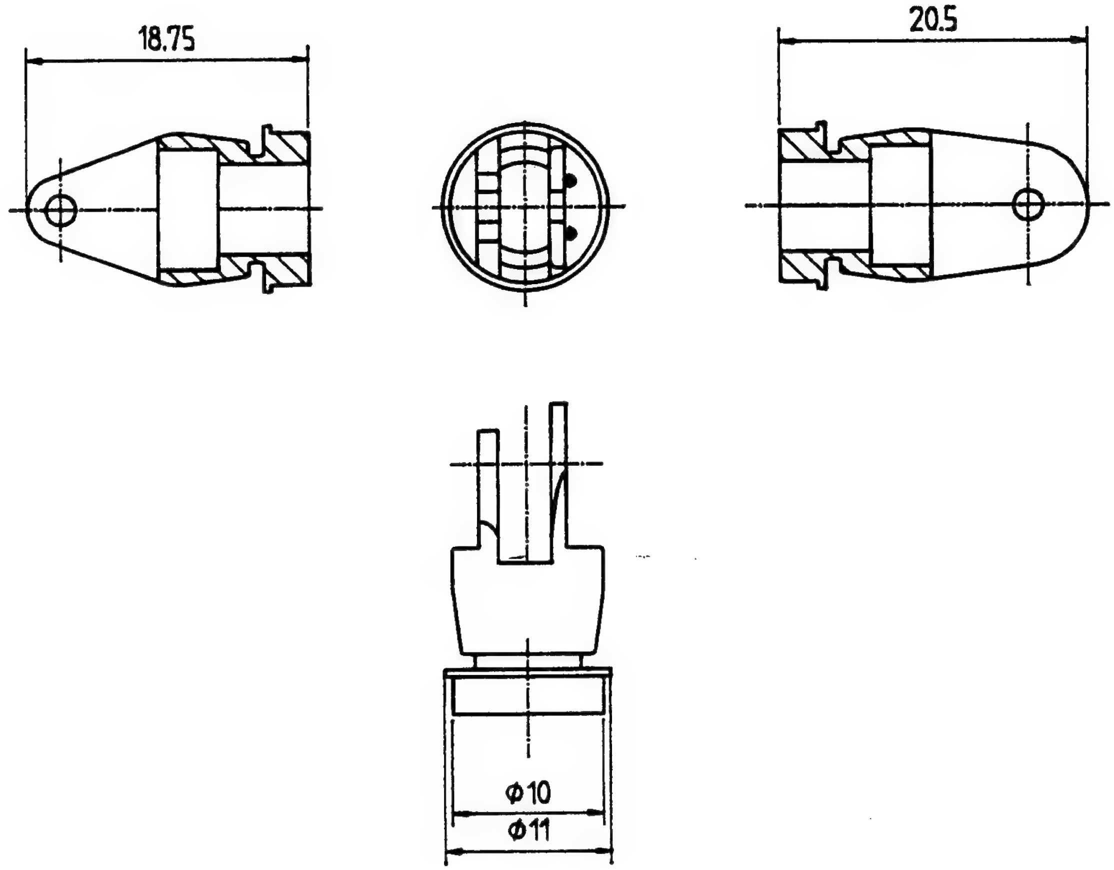

Fig. 3.c.32

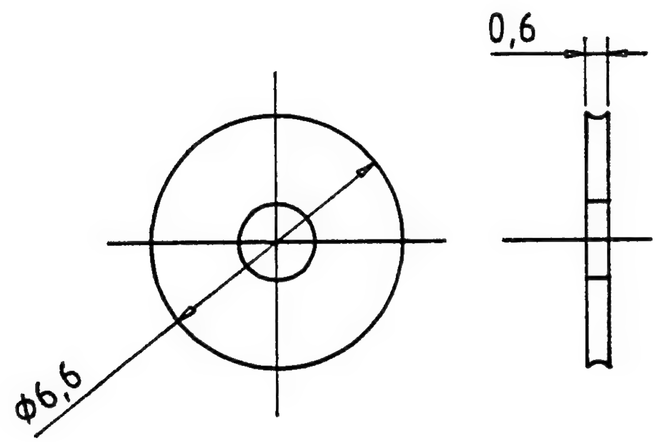

Fig. 3.c.33

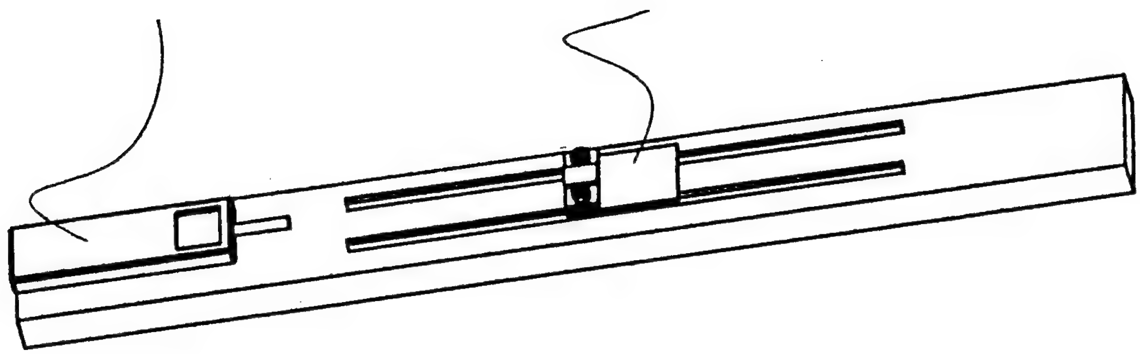

Fig. 3.d.1

Fig. 3.d.2

Fig. 3.d.3

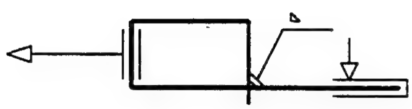

Fig. 3.d.4

Fig. 3.d.5

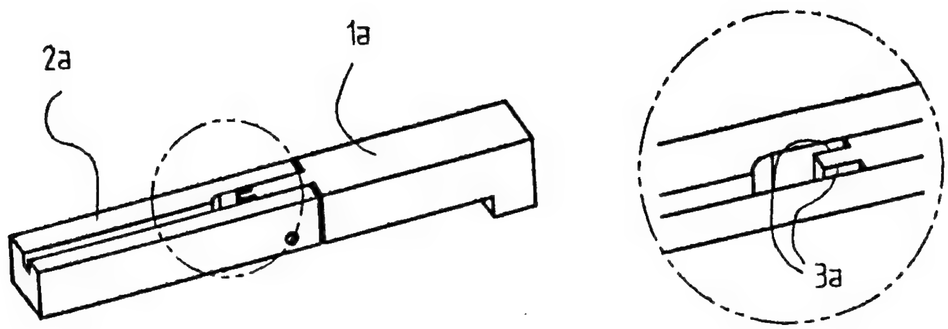

Fig. 3.d.6

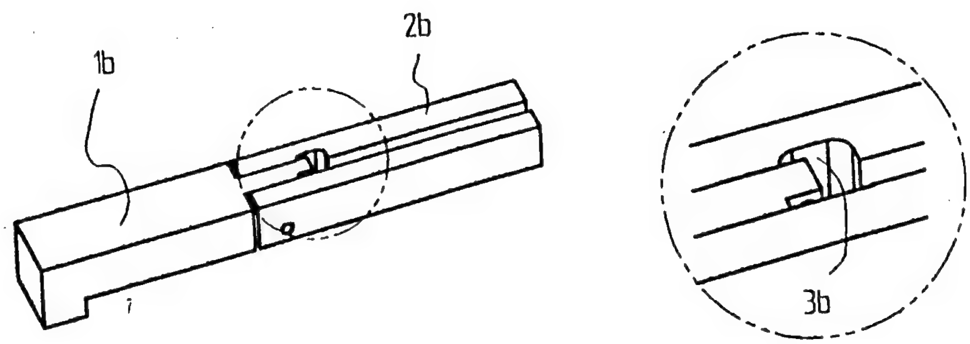

Fig. 3.d.7

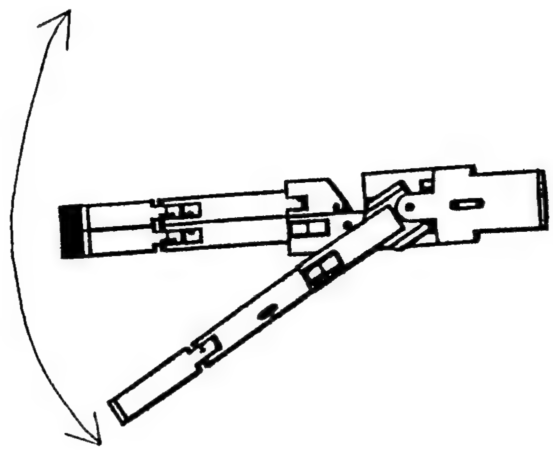

Fig. 3.d.8

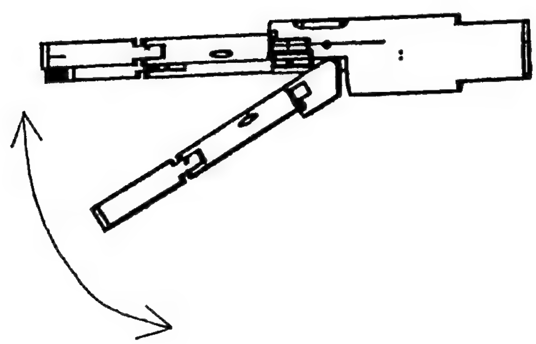

Fig. 3.d.9

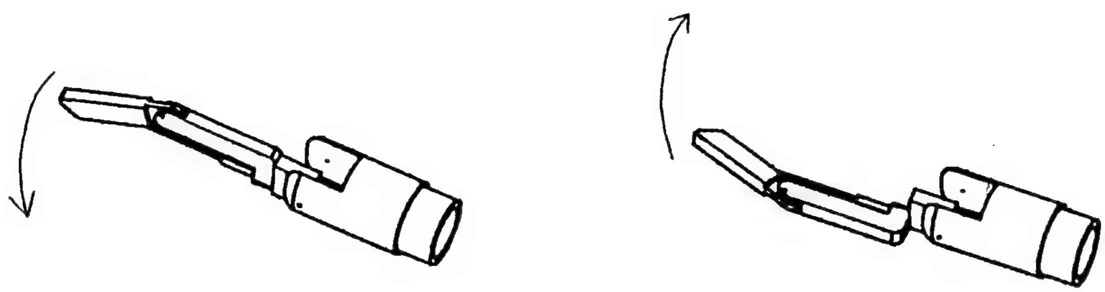

Fig. 3.d.10

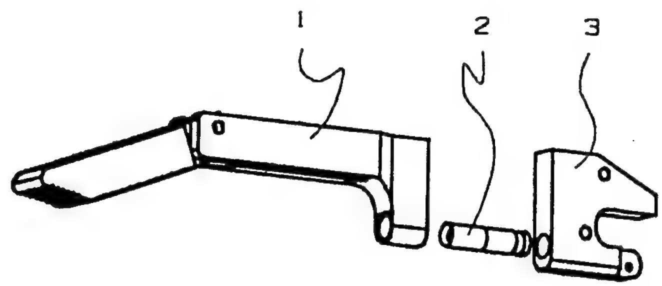

Fig. 3.d.11

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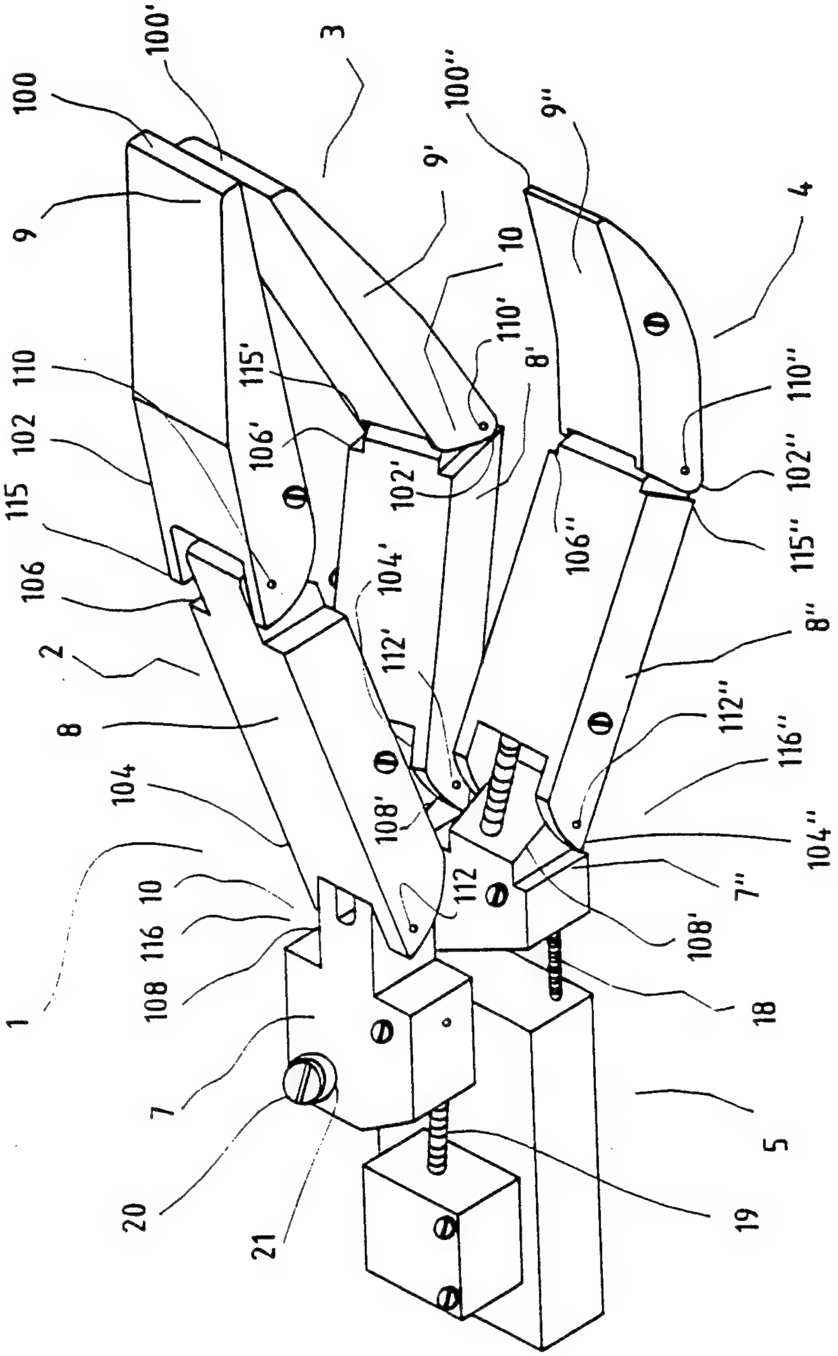

Fig. 3.d.12

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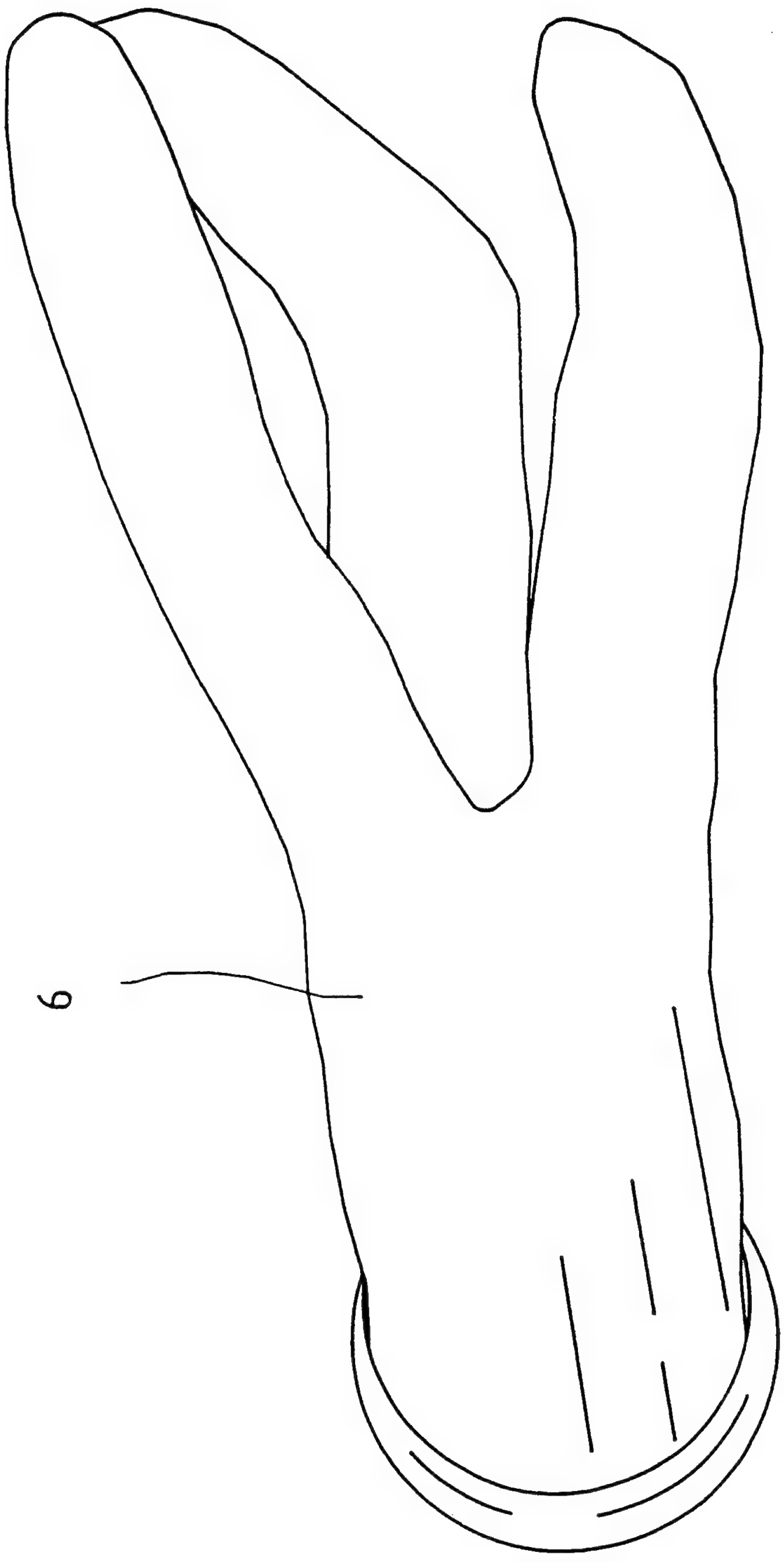


Fig. 3.d.13

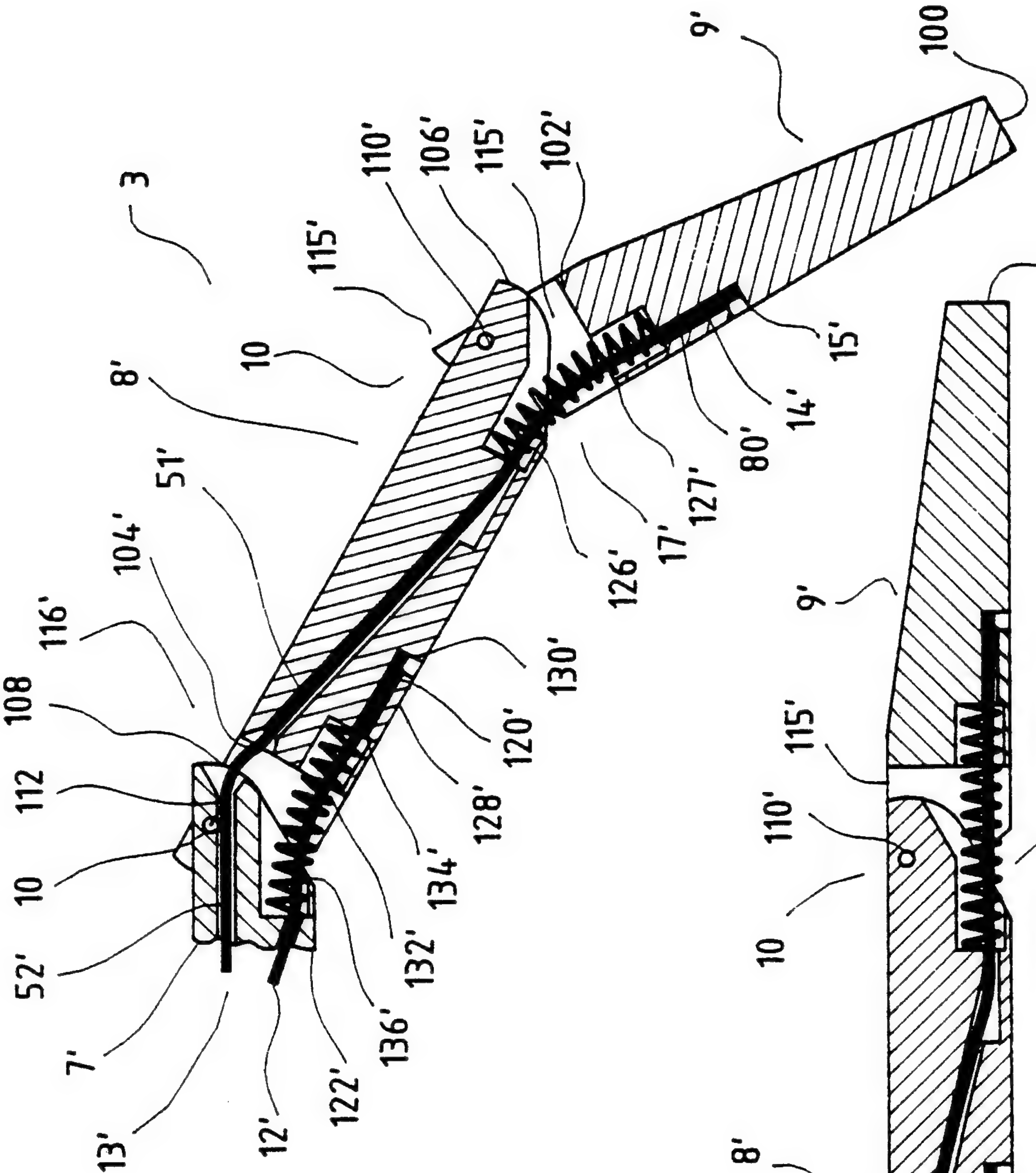


Fig. 3.d.14.a

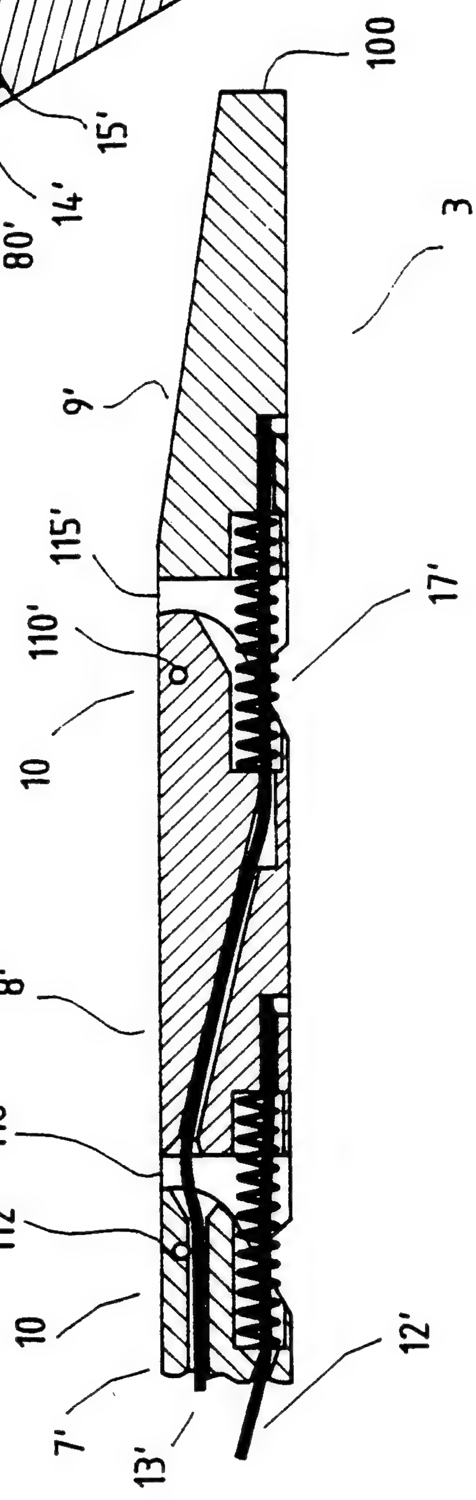


Fig. 3.d.14.b

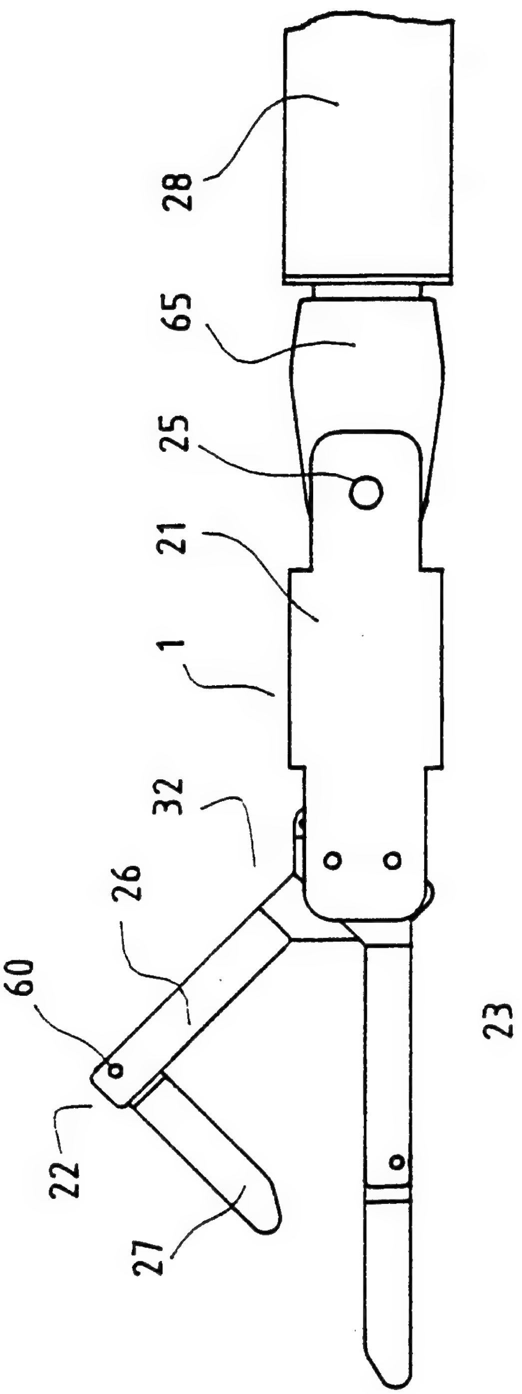


Fig. 3.d.15.a

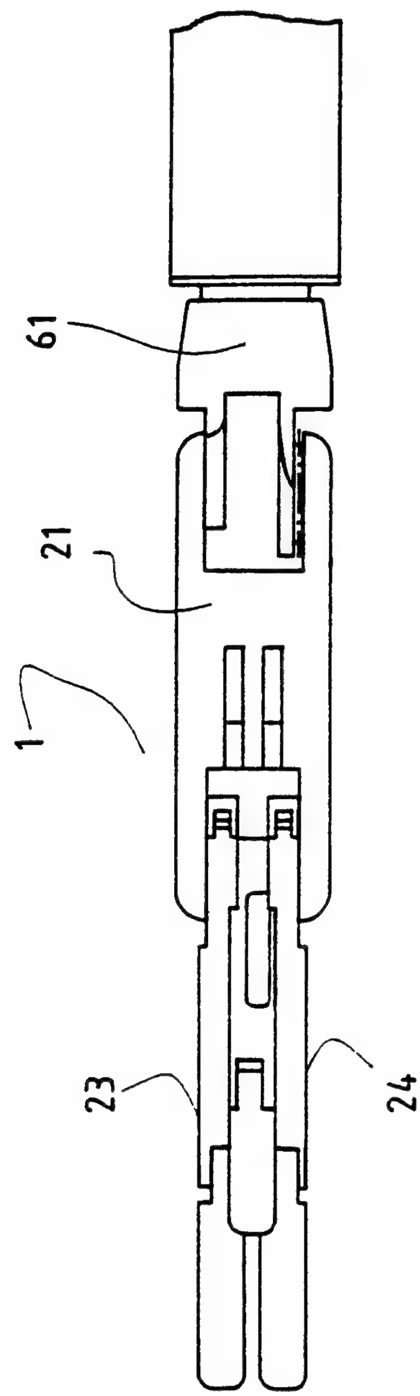


Fig. 3.d.15.b

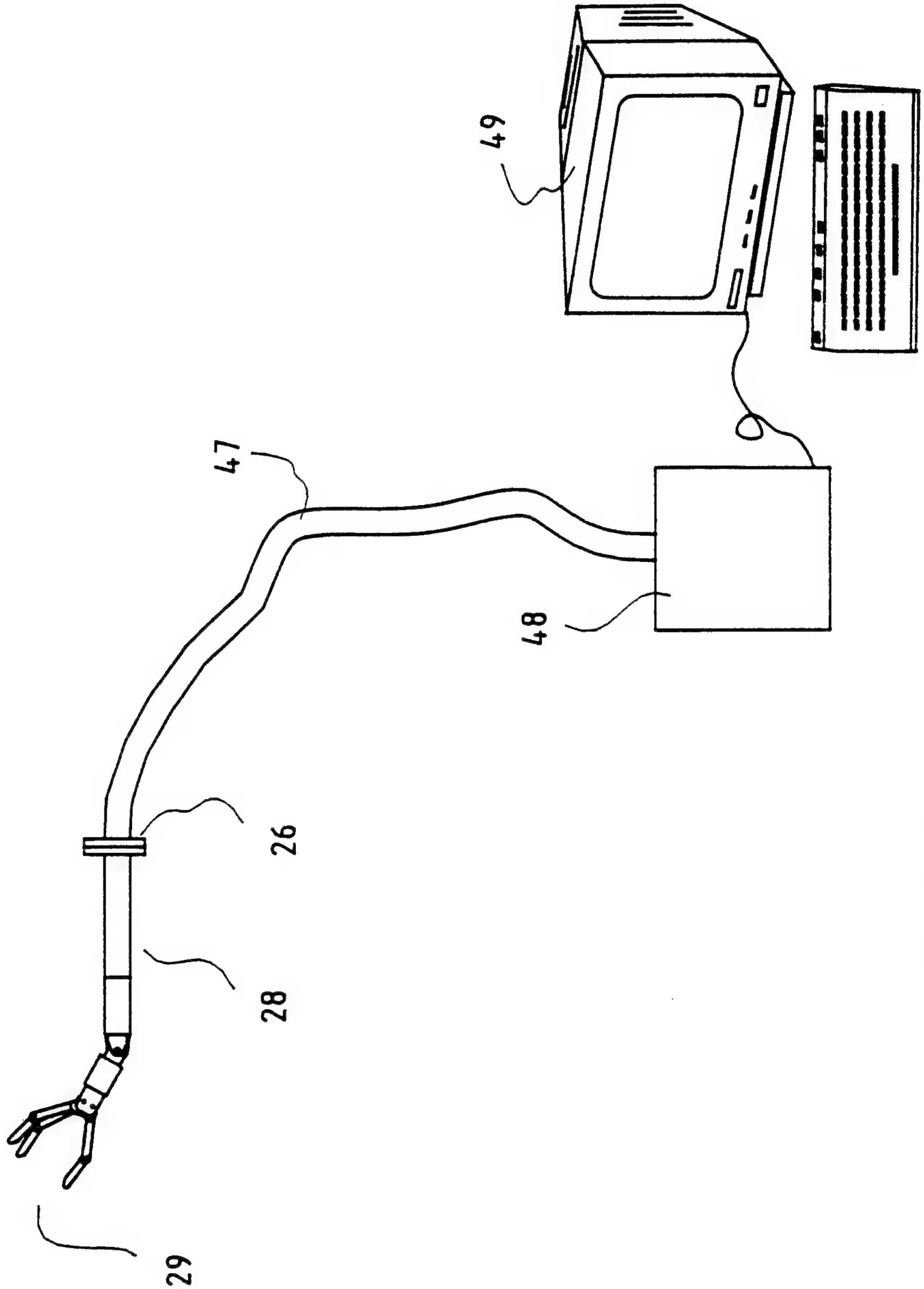


Fig. 3.d.16

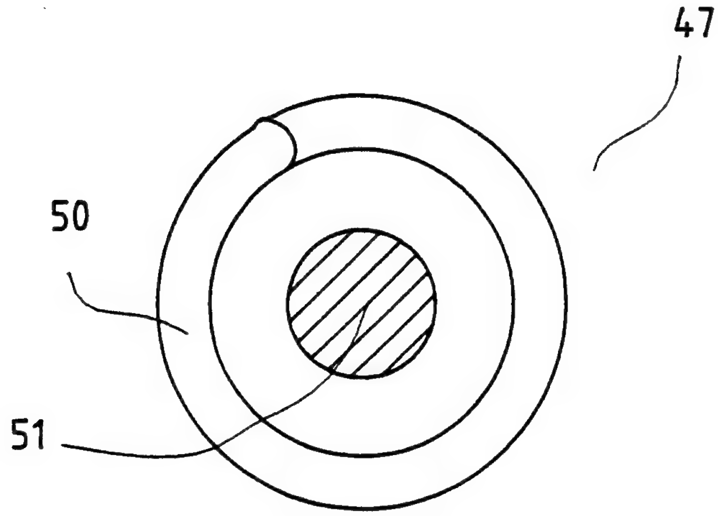


Fig. 3.d.17

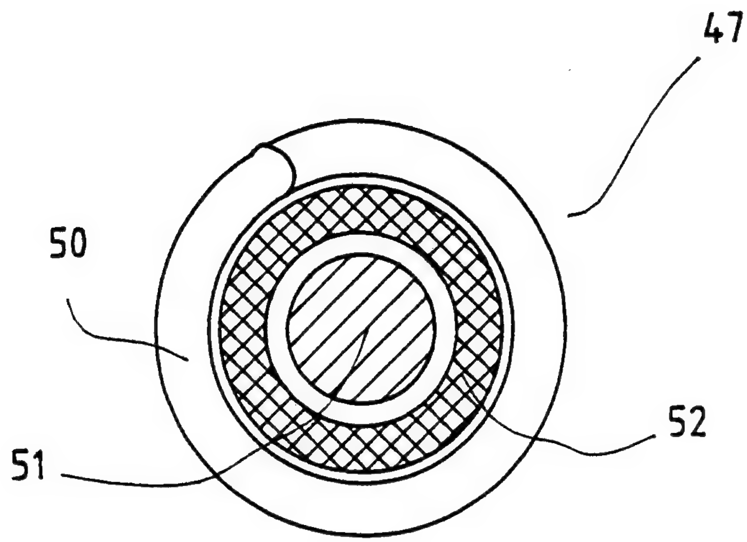
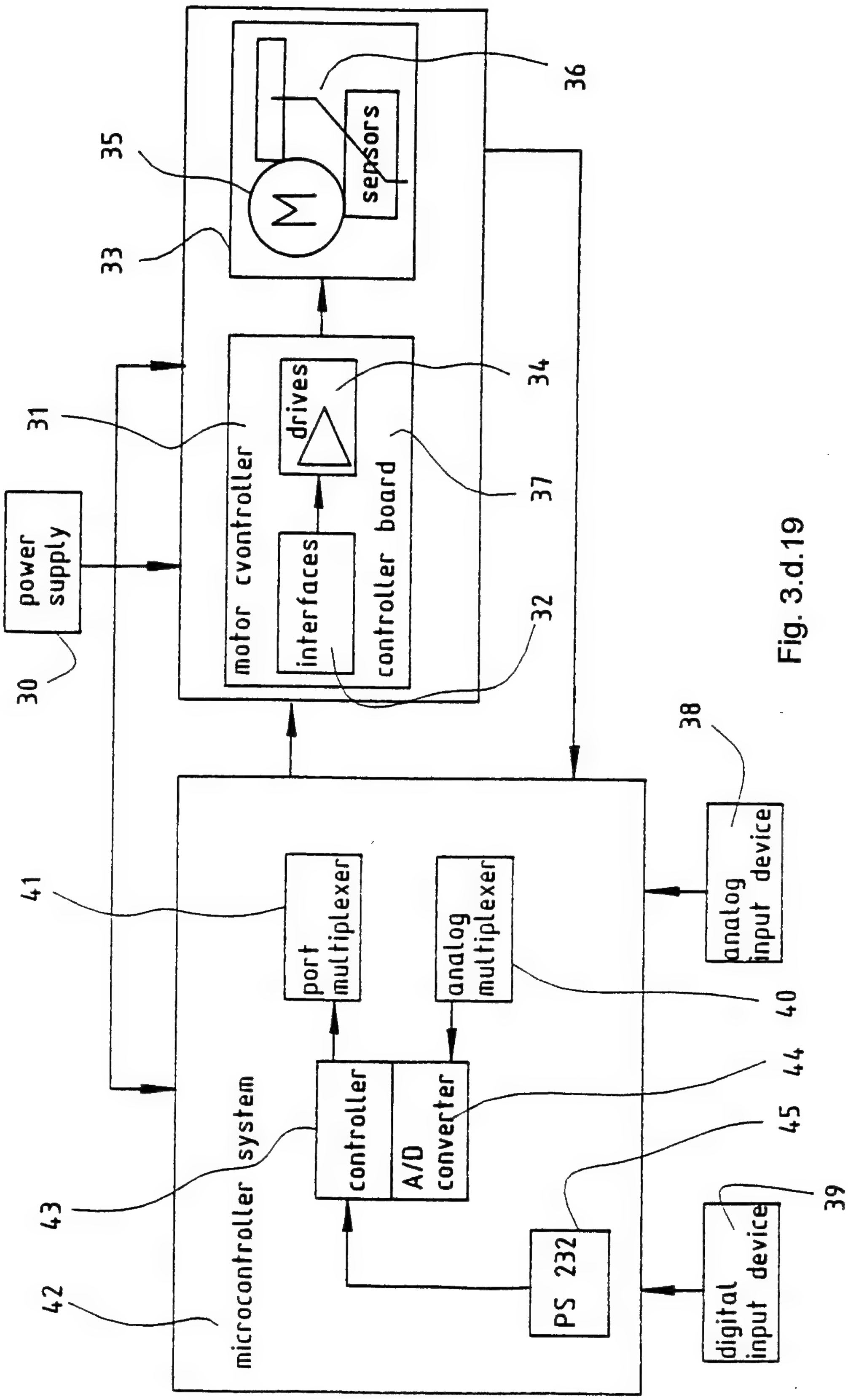


Fig. 3.d.18


power supply
motor cvontroller
interfaces
drives
controller board
M
sensors
microcontroller system
controller
A/D converter
port multiplexer
analog multiplexer
PS 232
analog input device
digital input device
30
31
32
33
34
35
36
37
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39
40
41
42
43
44
45

Fig. 3.d.19

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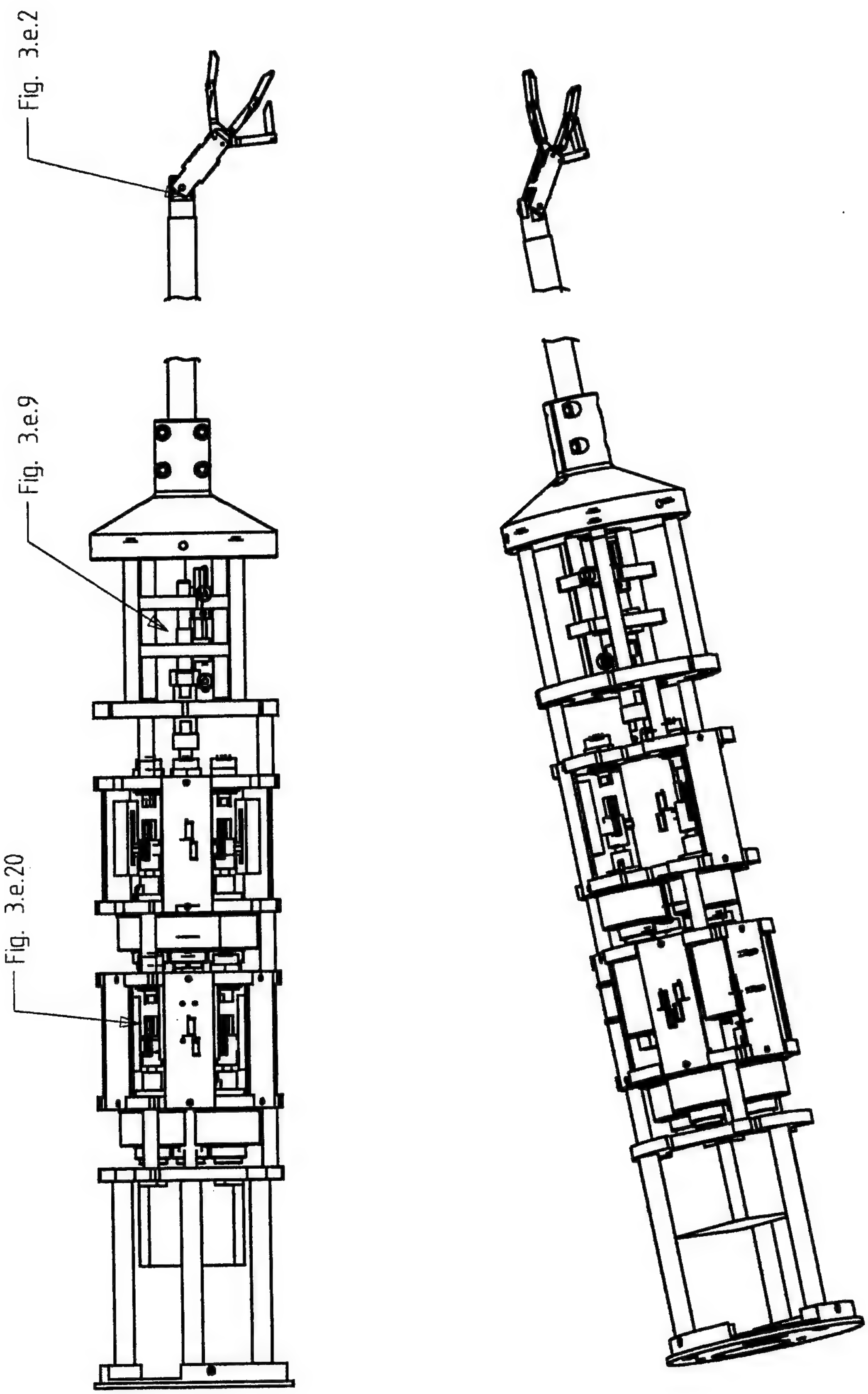


Fig. 3.e.1

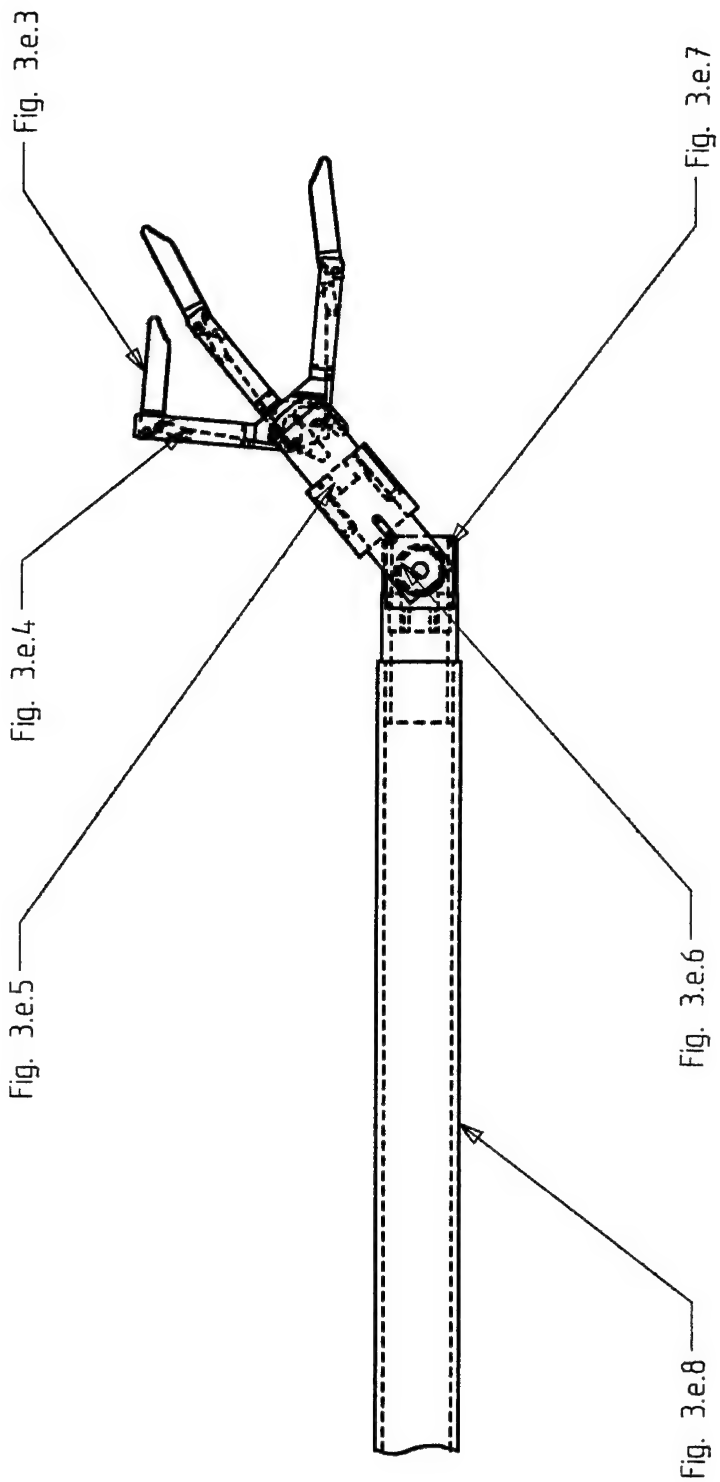
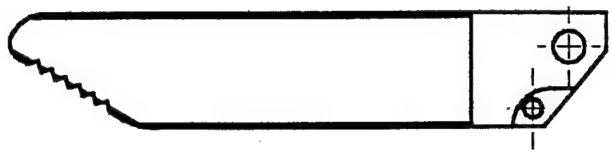


Fig. 3.e.2



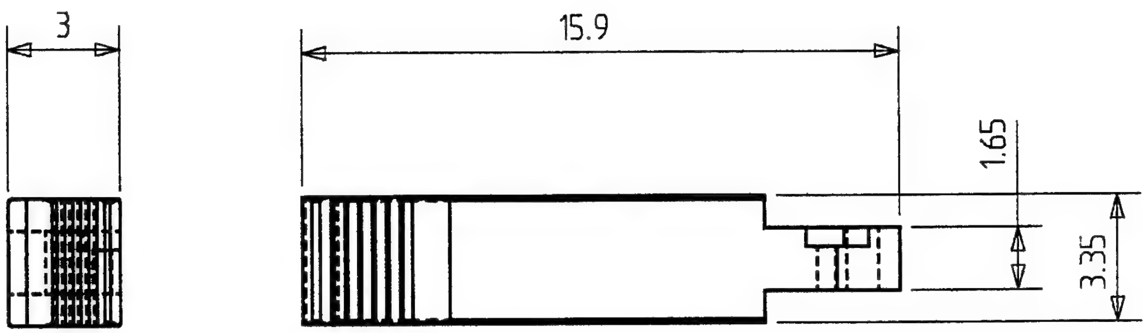


Fig. 3.e.3

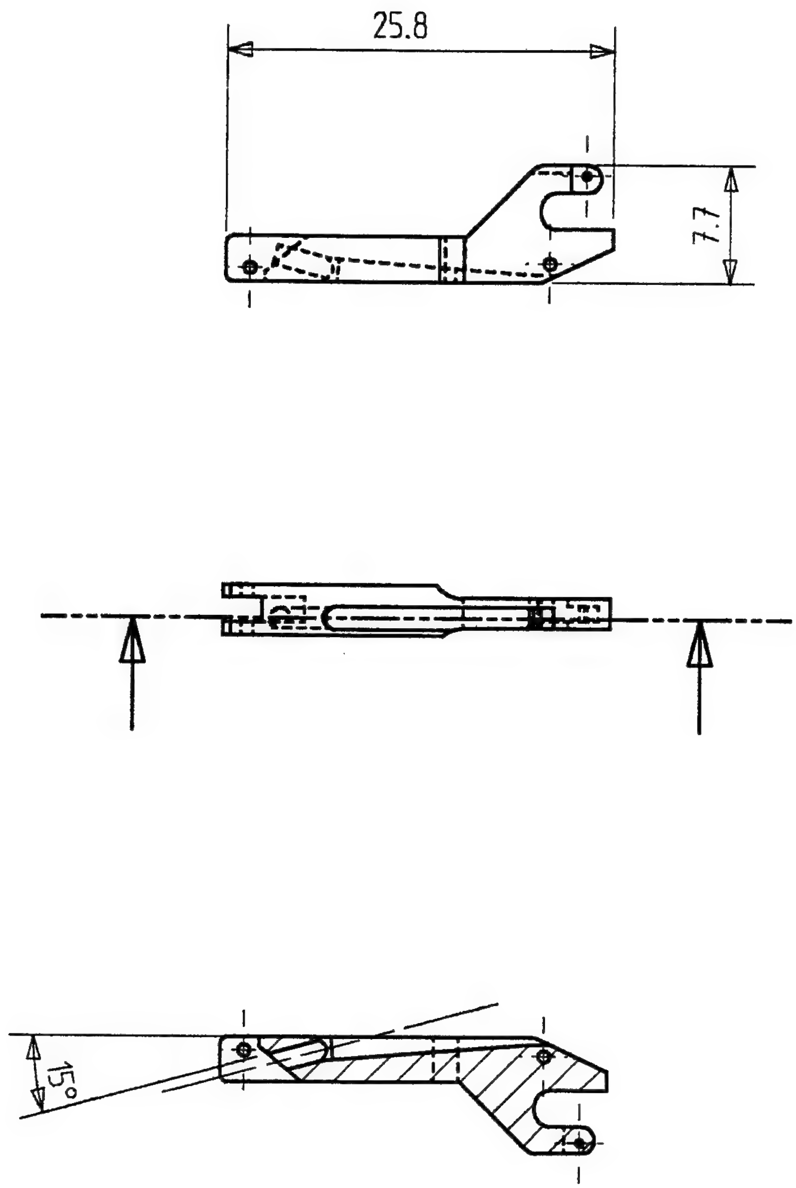


Fig. 3.e.4

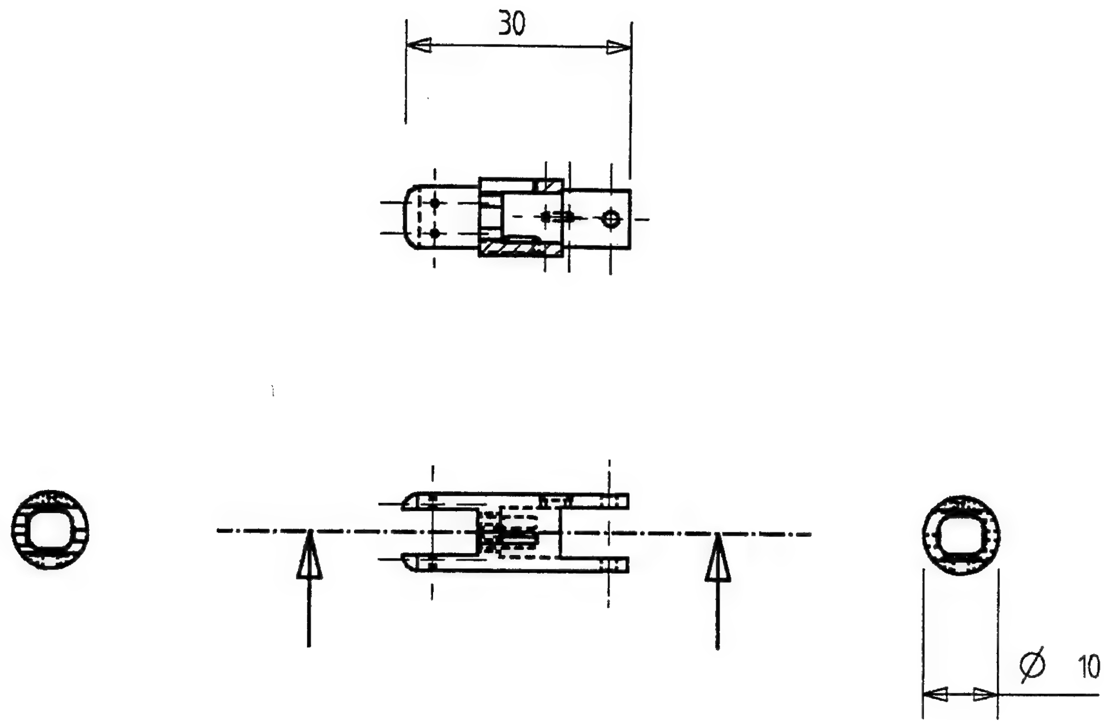


Fig. 3.e.5

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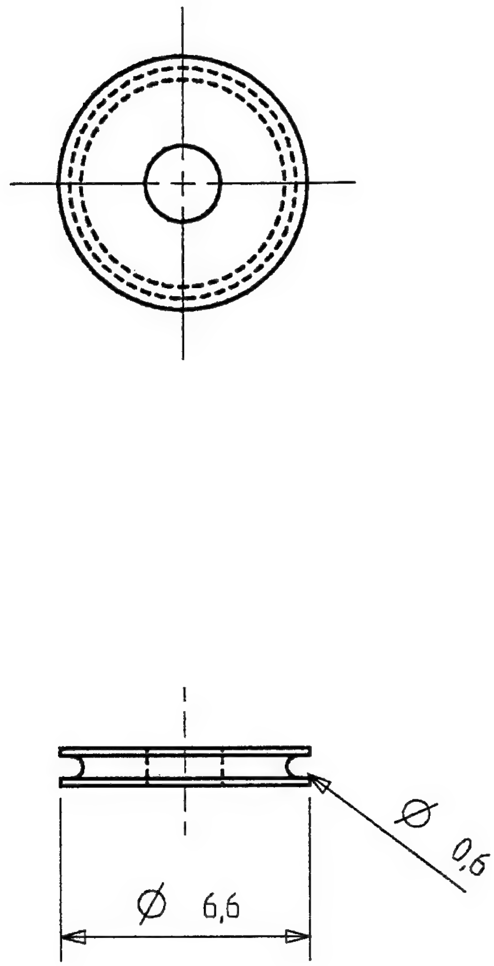


Fig. 3.e.6

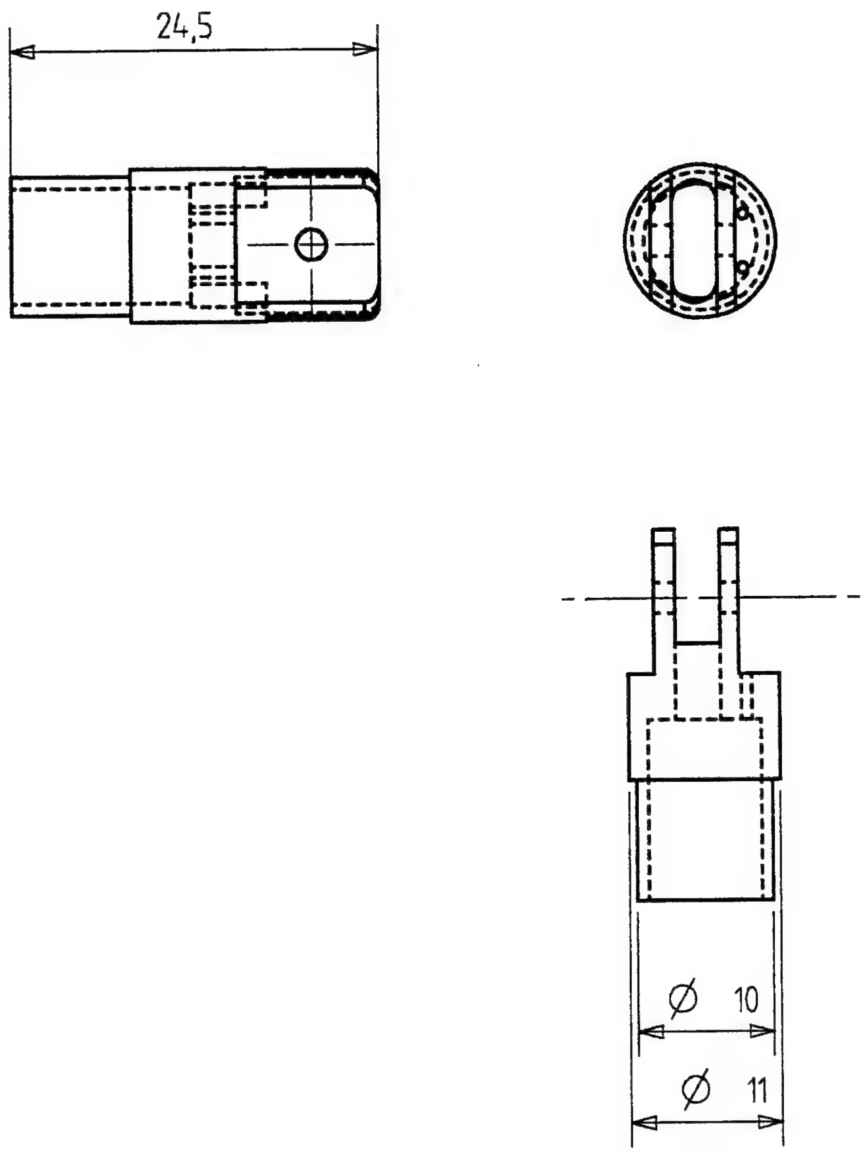


Fig. 3.e.7

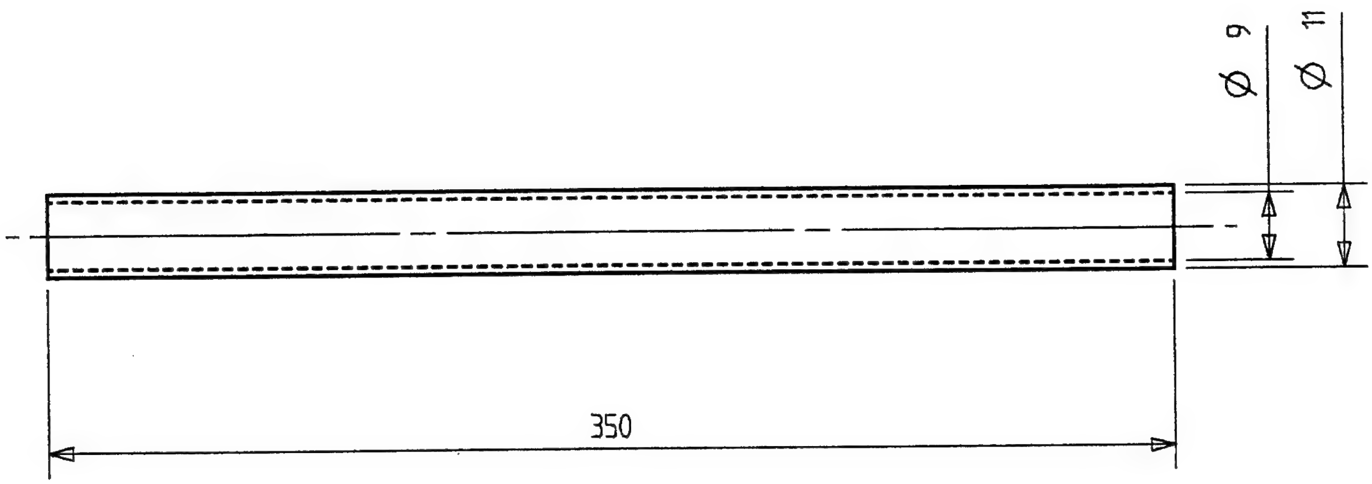


Fig. 3.e.8

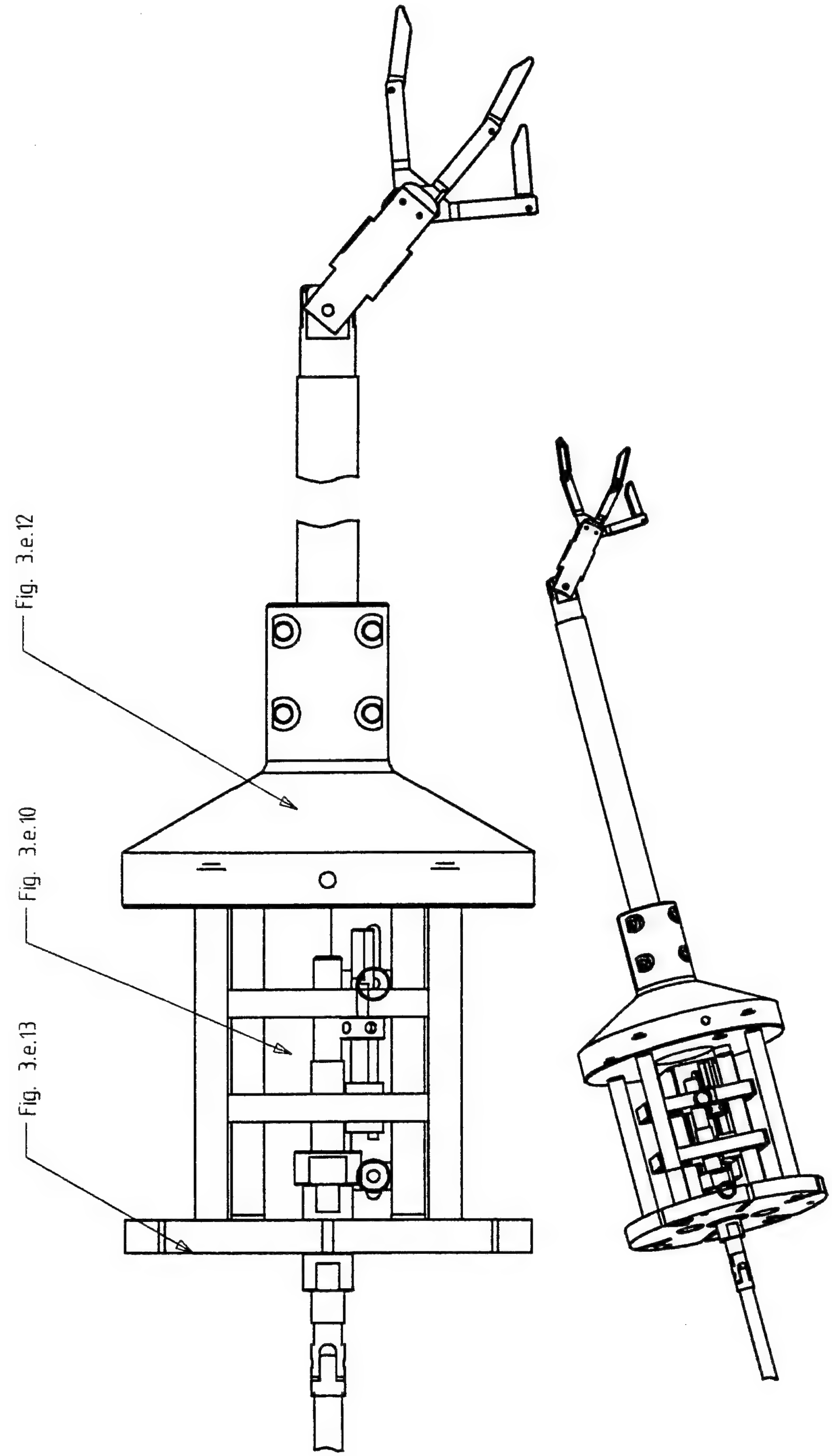


Fig. 3.e.9

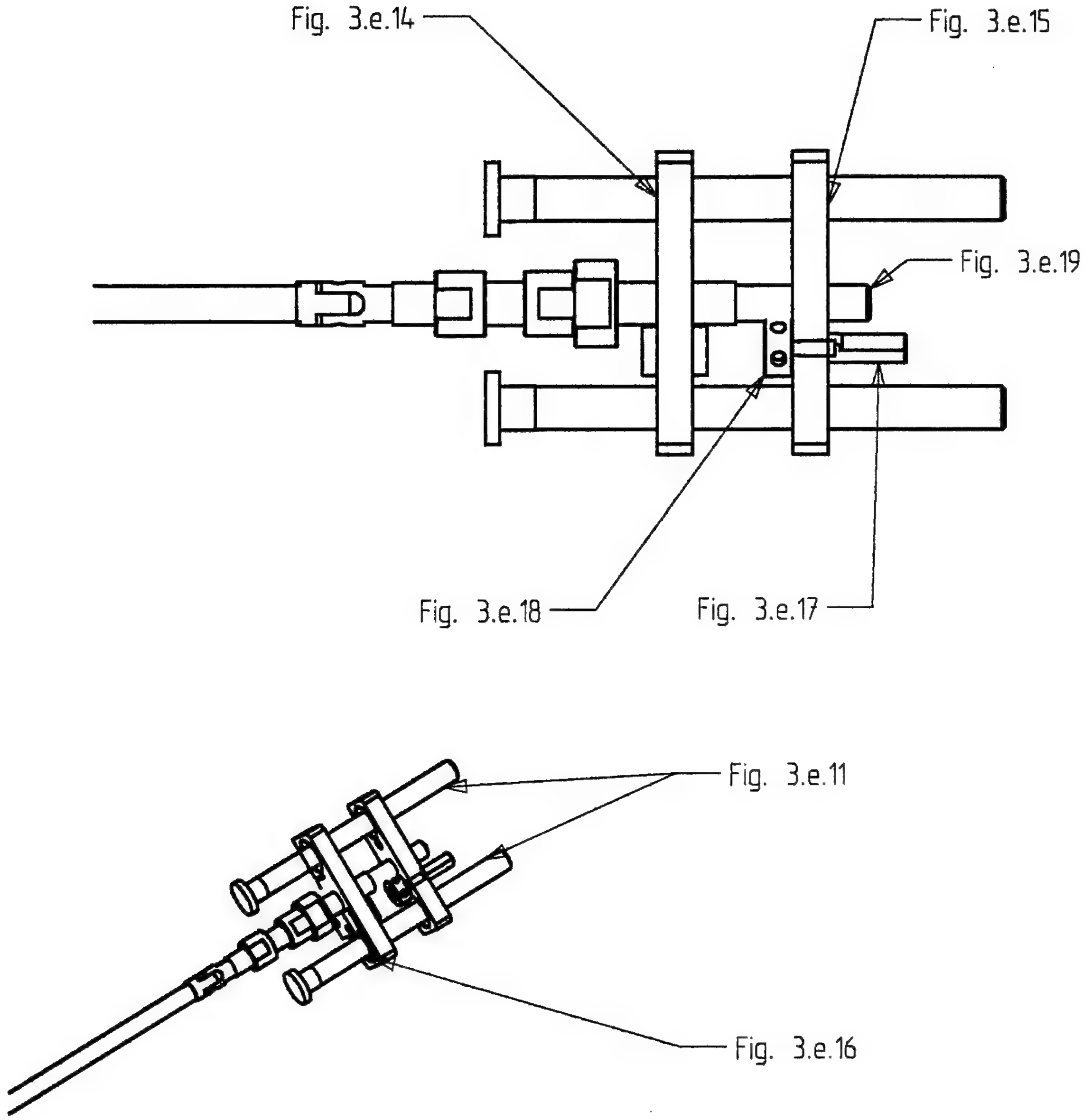
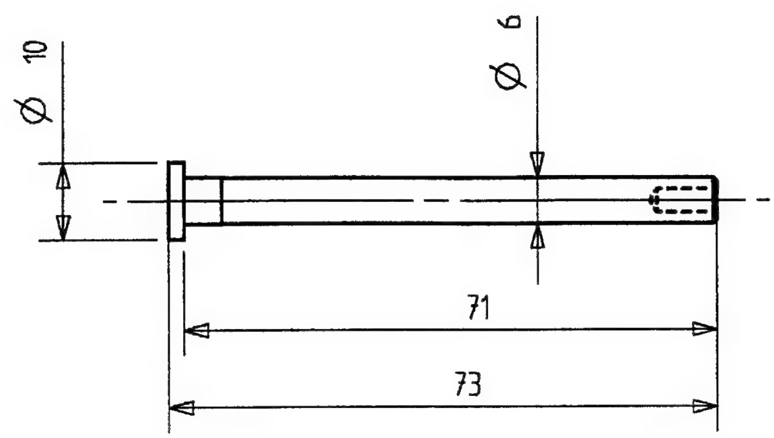


Fig. 3.e.10



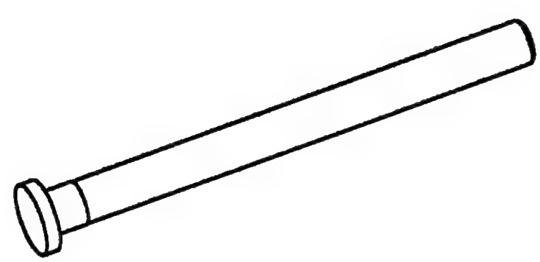
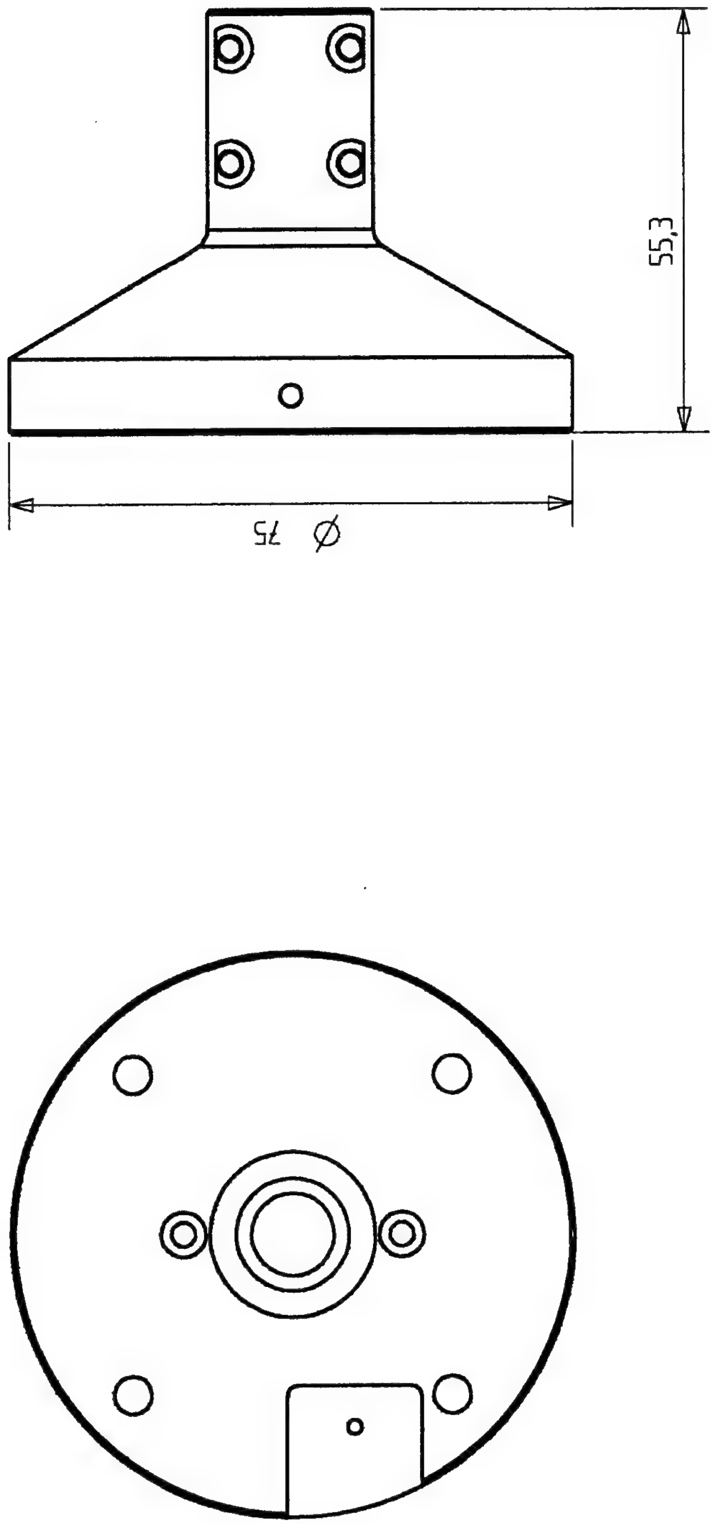


Fig. 3.e.11



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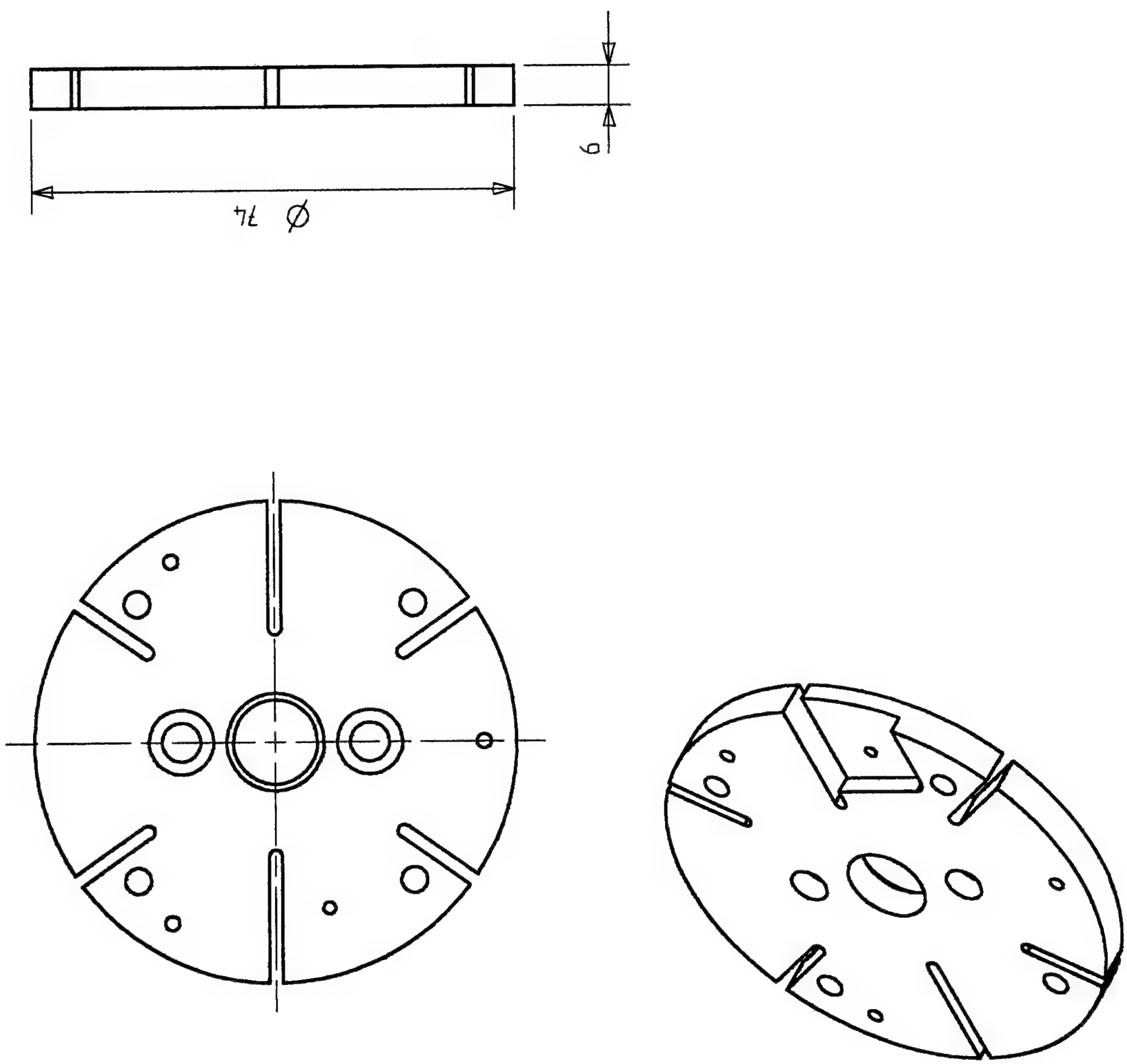
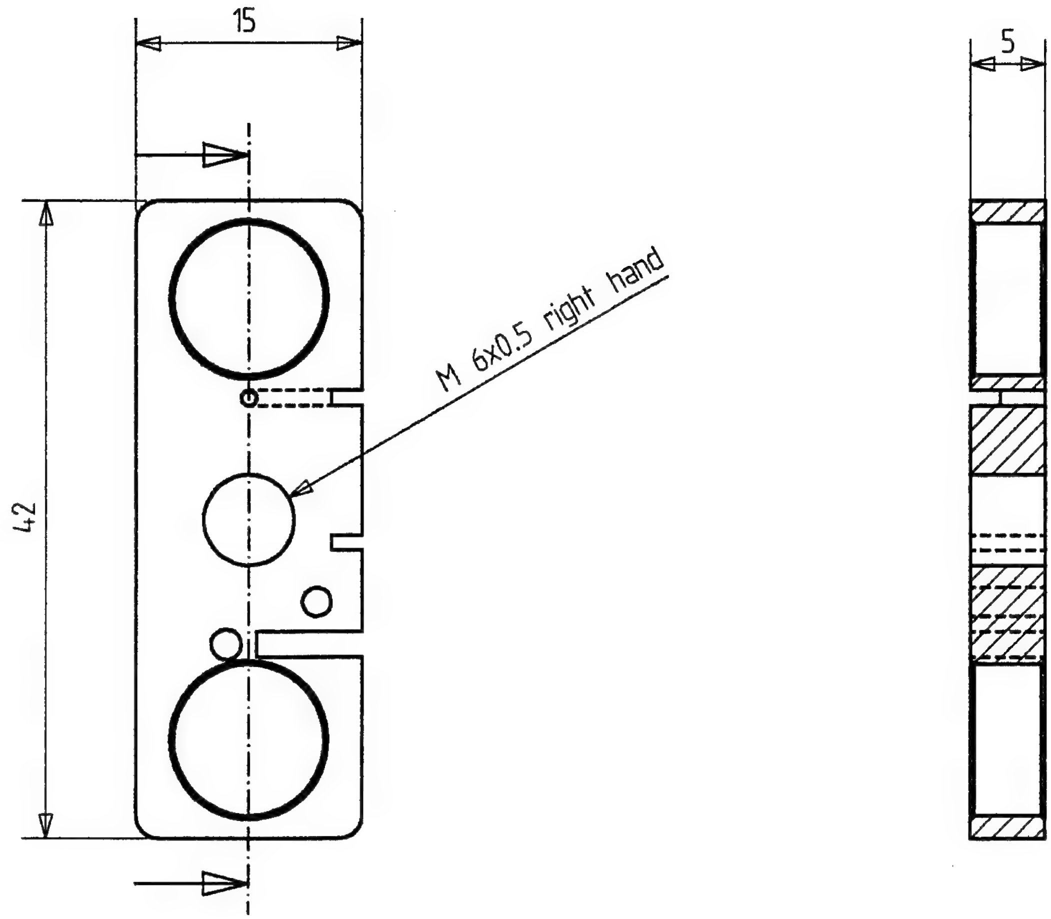


Fig. 3.e.13



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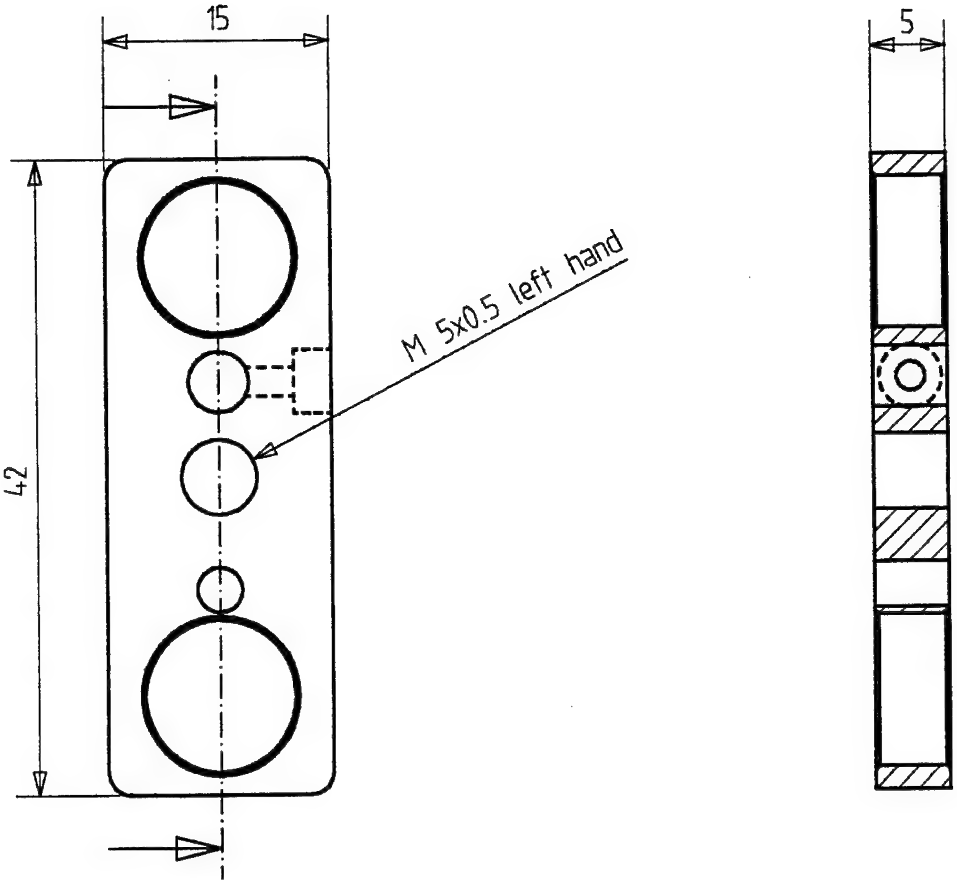

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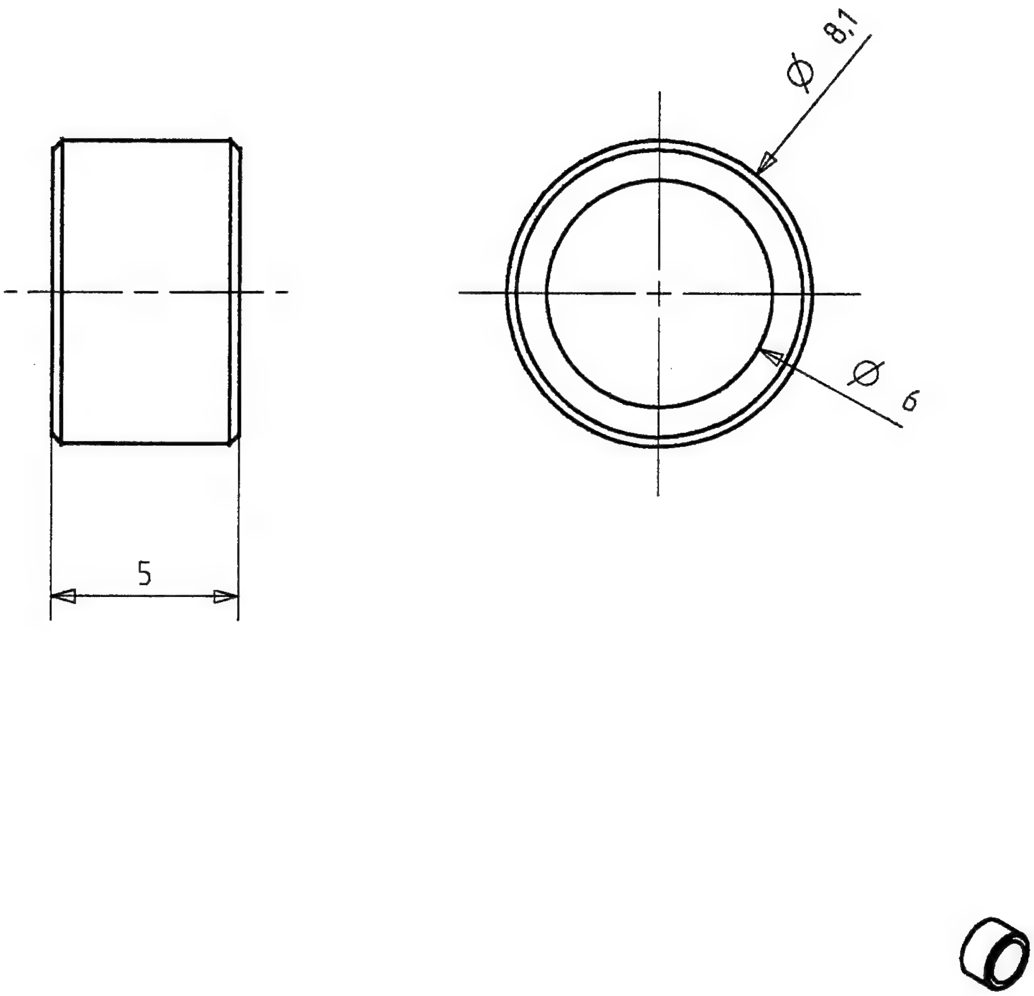


Fig. 3.e.16

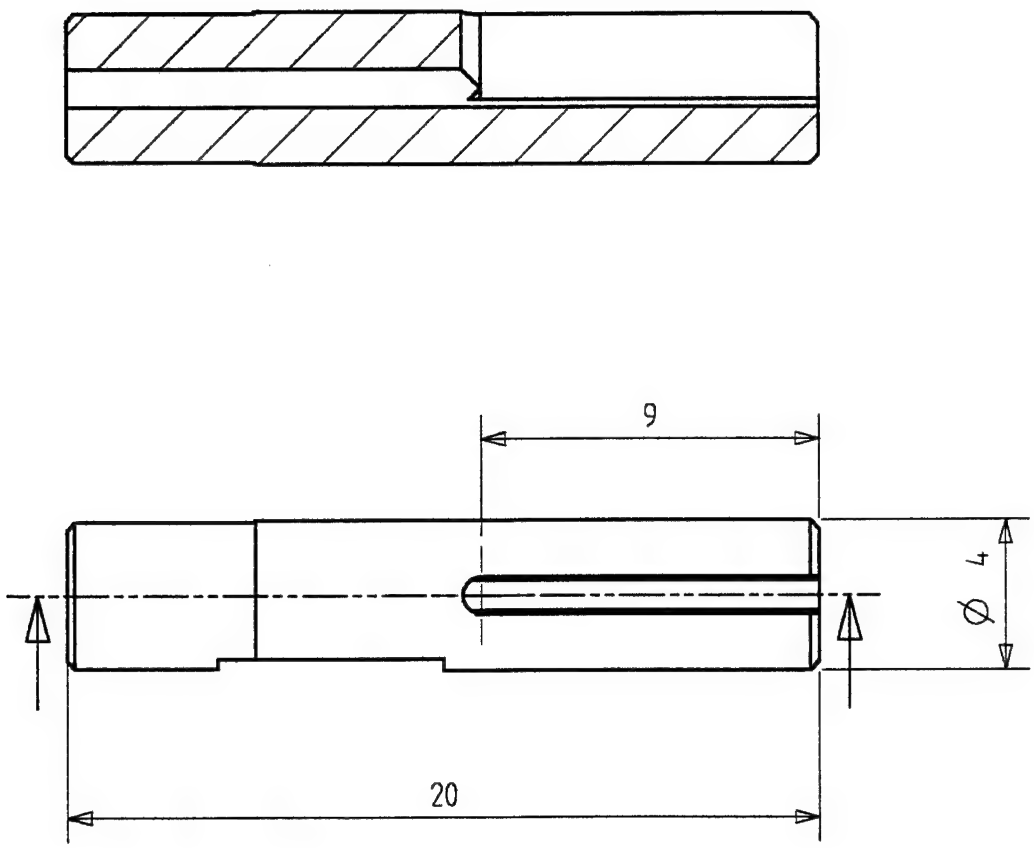


Fig. 3.e.17

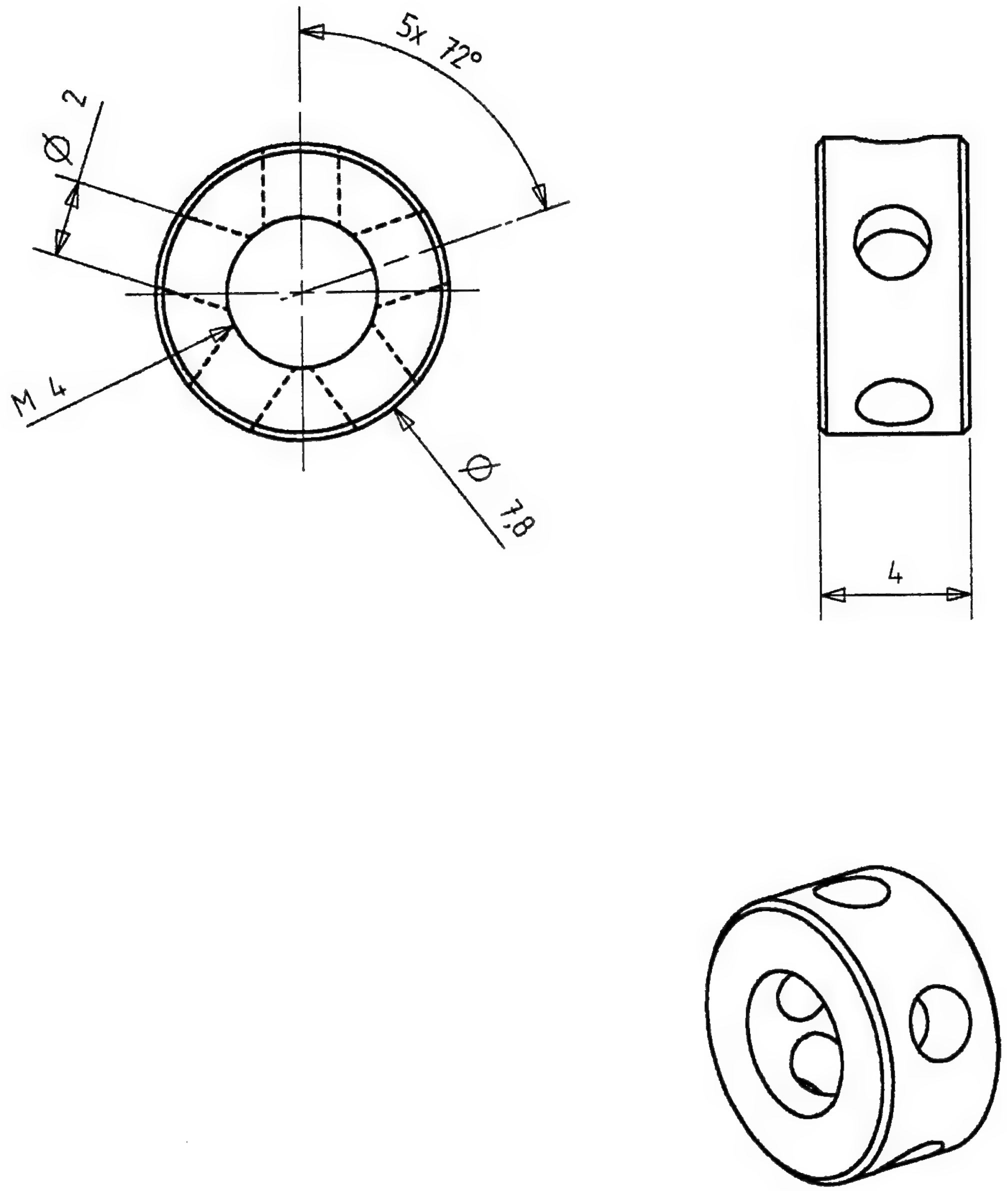
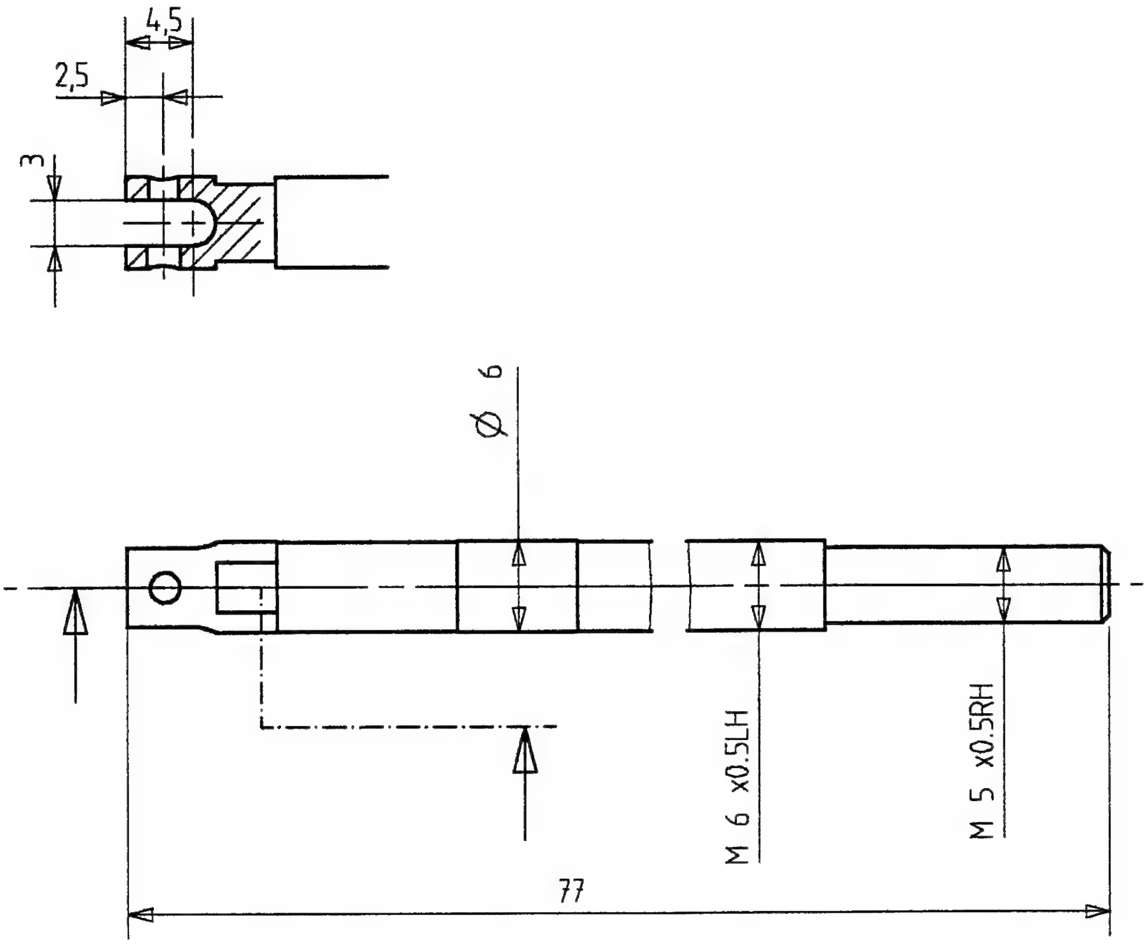


Fig. 3.e.18



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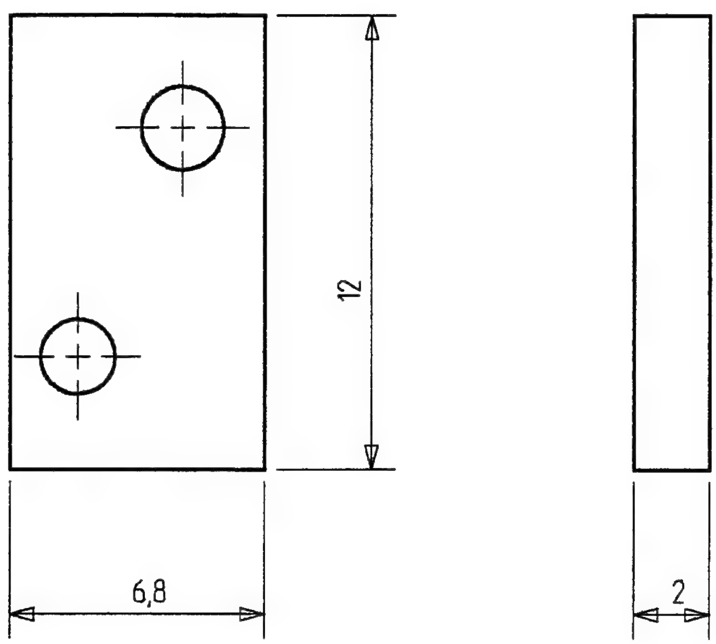


Fig. 3.e.20

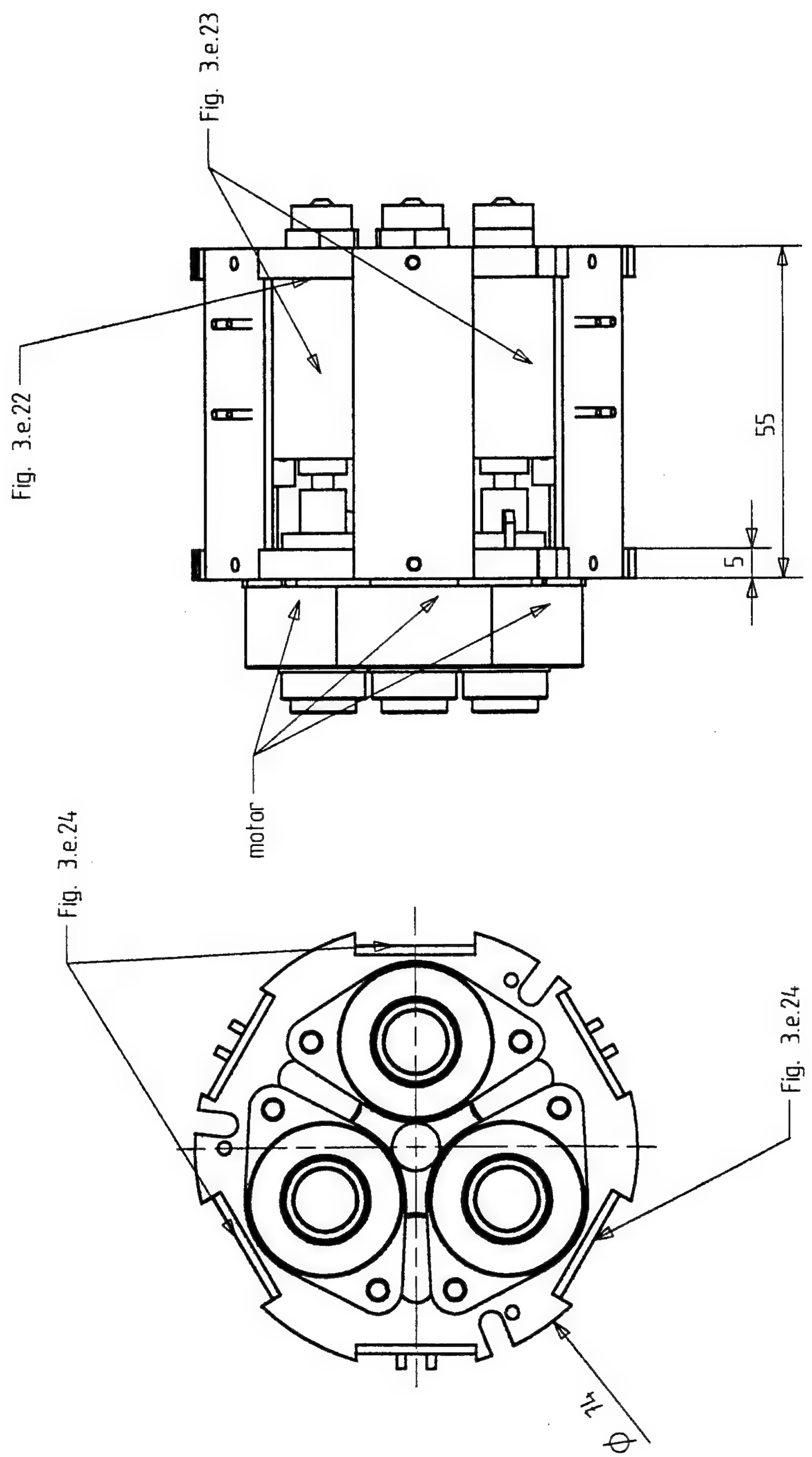


Fig. 3.e.21

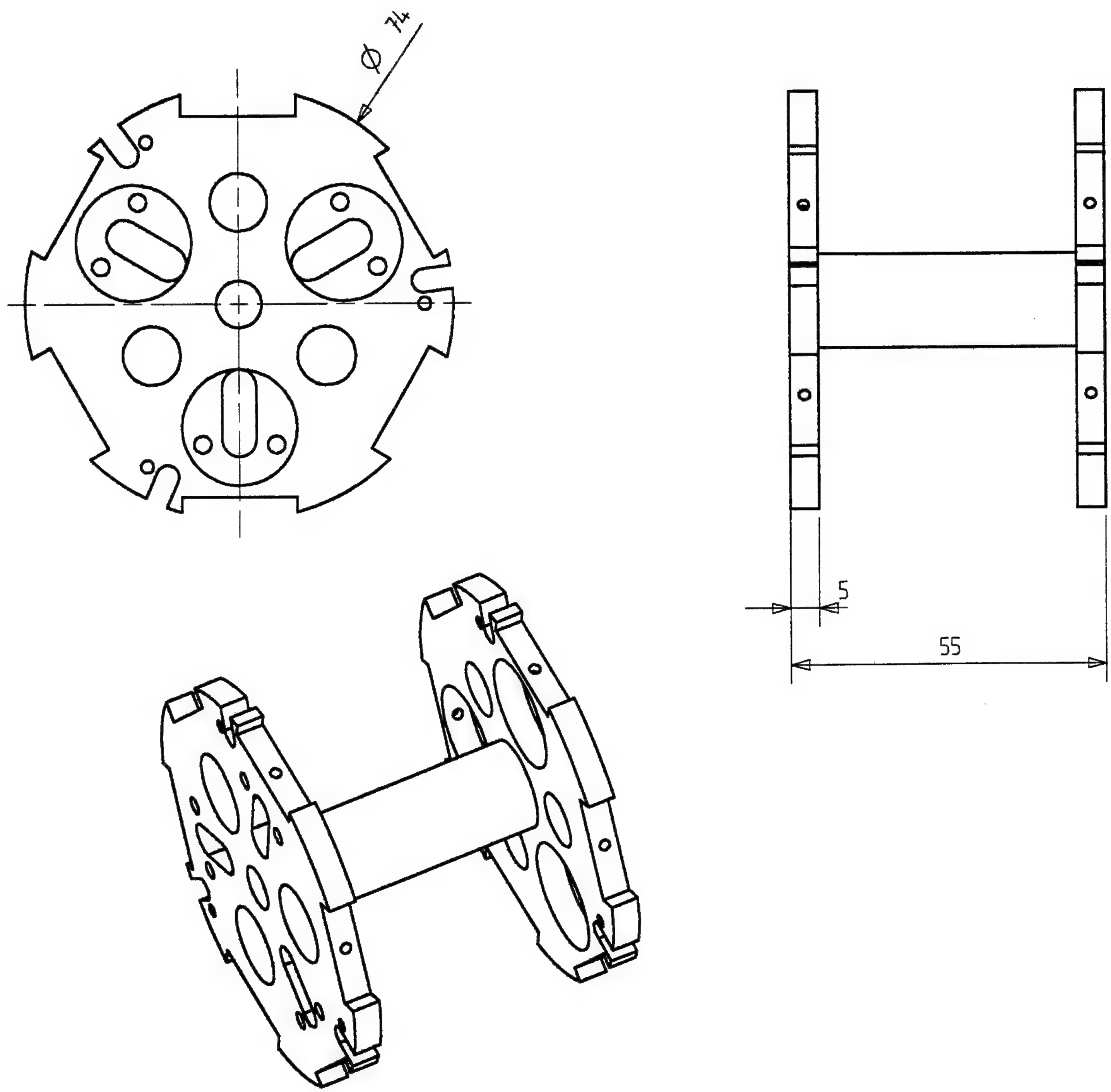


Fig. 3.e.22

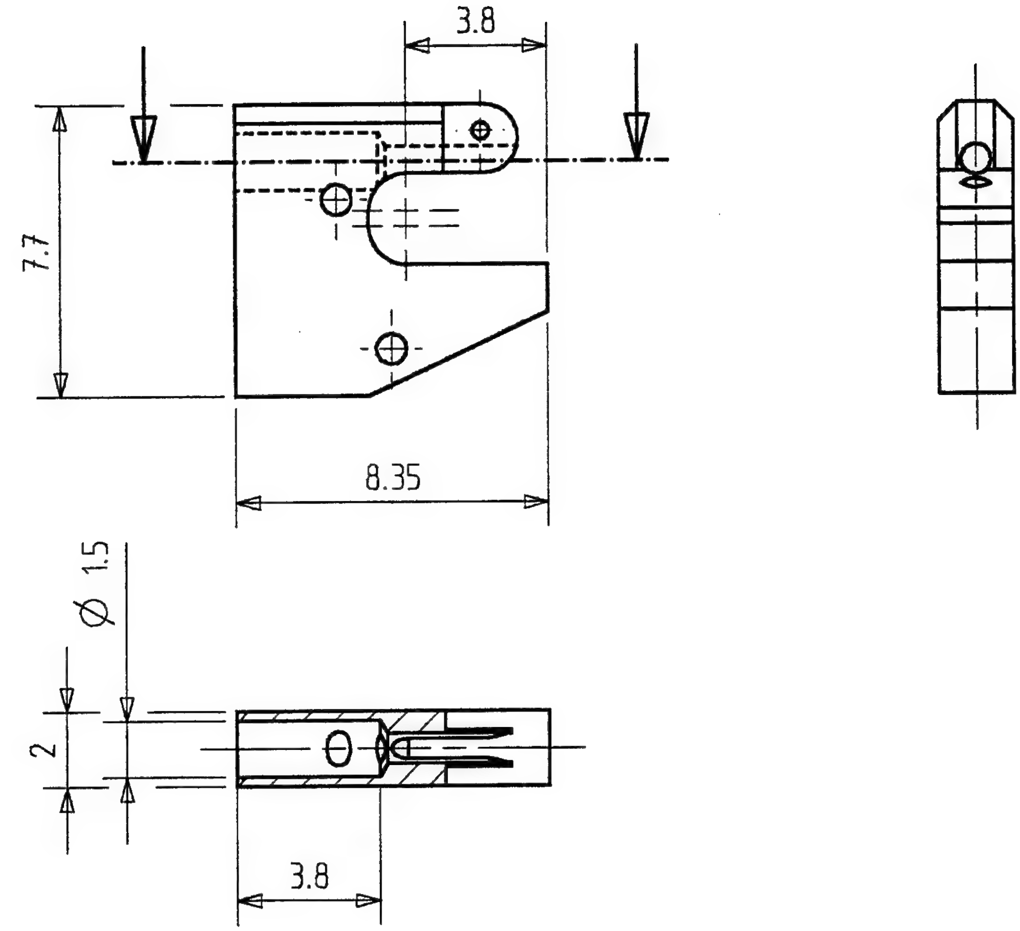


Fig. 3.f.1

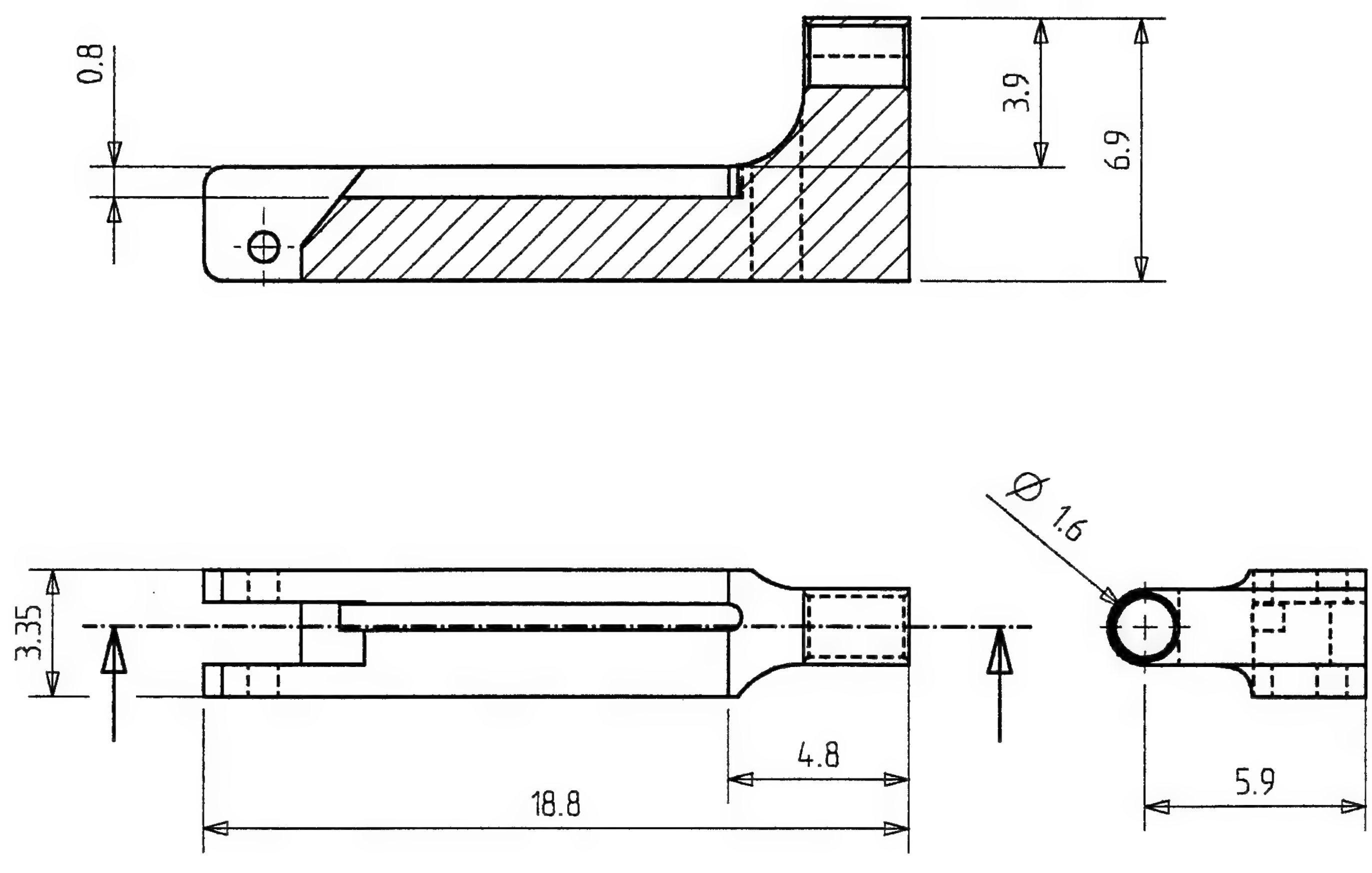


Fig. 3.f.2

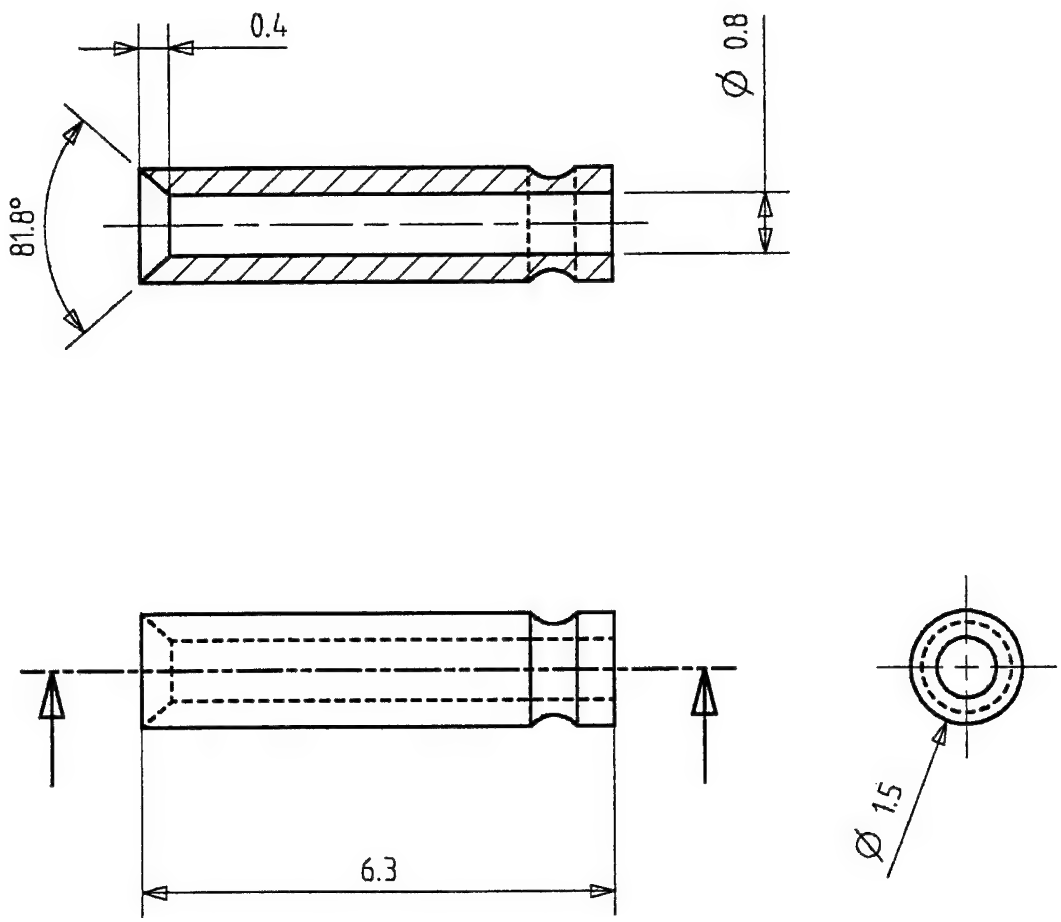


Fig. 3.f.3

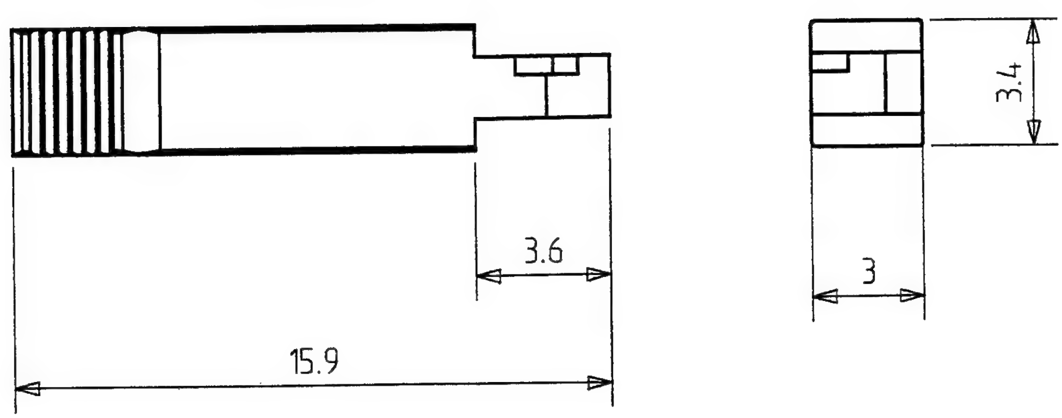


Fig. 3.f.4

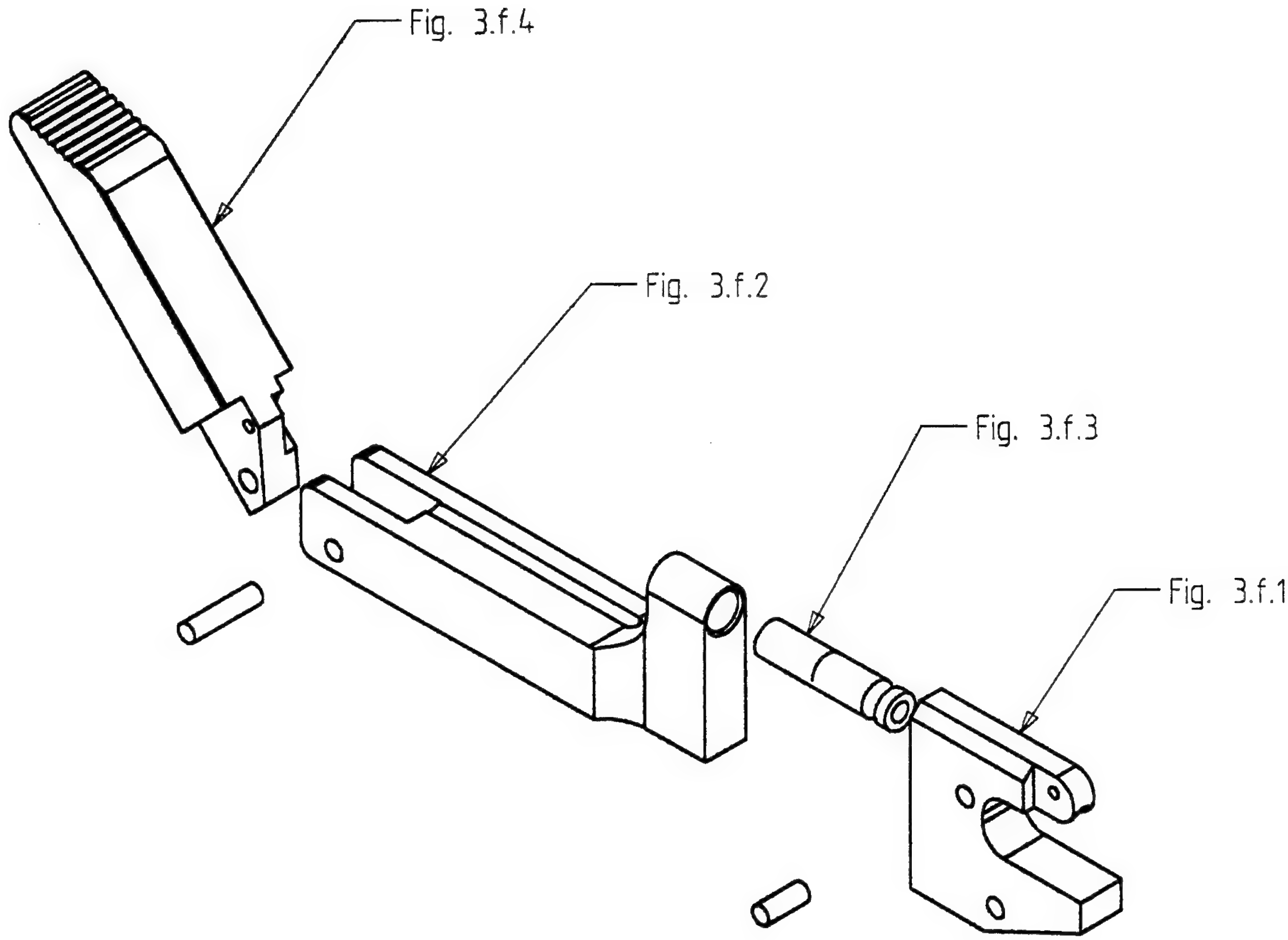
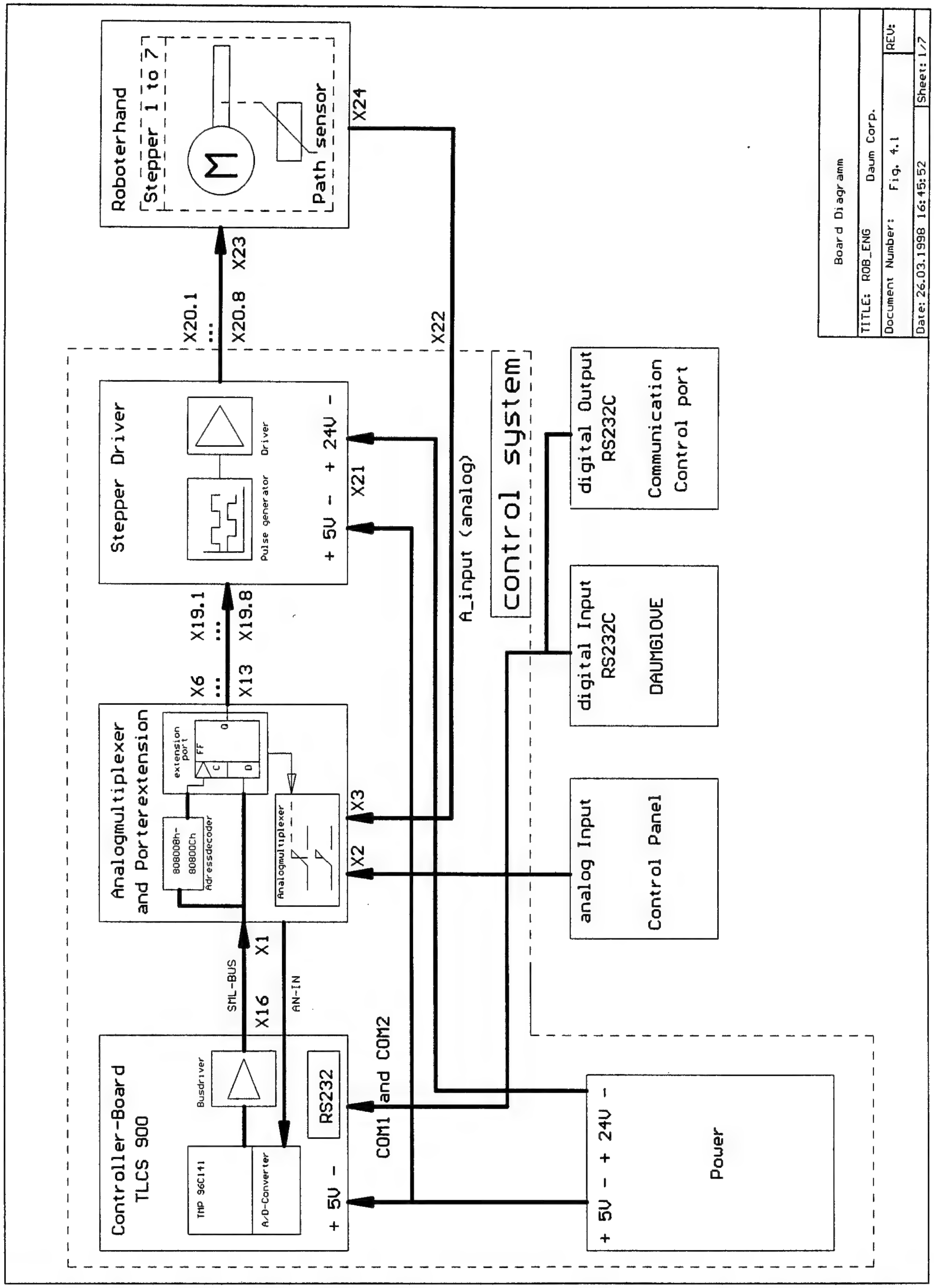


Fig. 3.f.5


Roboterhand
Stepper 1 to 7
Path sensor
X24
X23
X20.1
X20.8
X22
Stepper Driver
Pulse generator
Driver
+ 5V - + 24V -
X21
A_input (analog)
control system
digital Output
RS232C
Communication
Control port
X19.1
X19.8
X6
X13
digital Input
RS232C
DAUMGlOVE
Analogmultiplexer
and Porterextension
extension port
FF
808008h-
80800Ch
Adressdecoder
Analogmultiplexer
X3
X2
analog Input
Control Panel
X1
SML-BUS
X16
AN-IN
Controller-Board
TLCS 900
Busdriver
TMP 96C141
A/D-Converter
RS232
+ 5V -
COM1 and COM2
+ 5V - + 24V -
Power
Board Diagramm
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Daum Corp.
Document Number: Fig. 4.1
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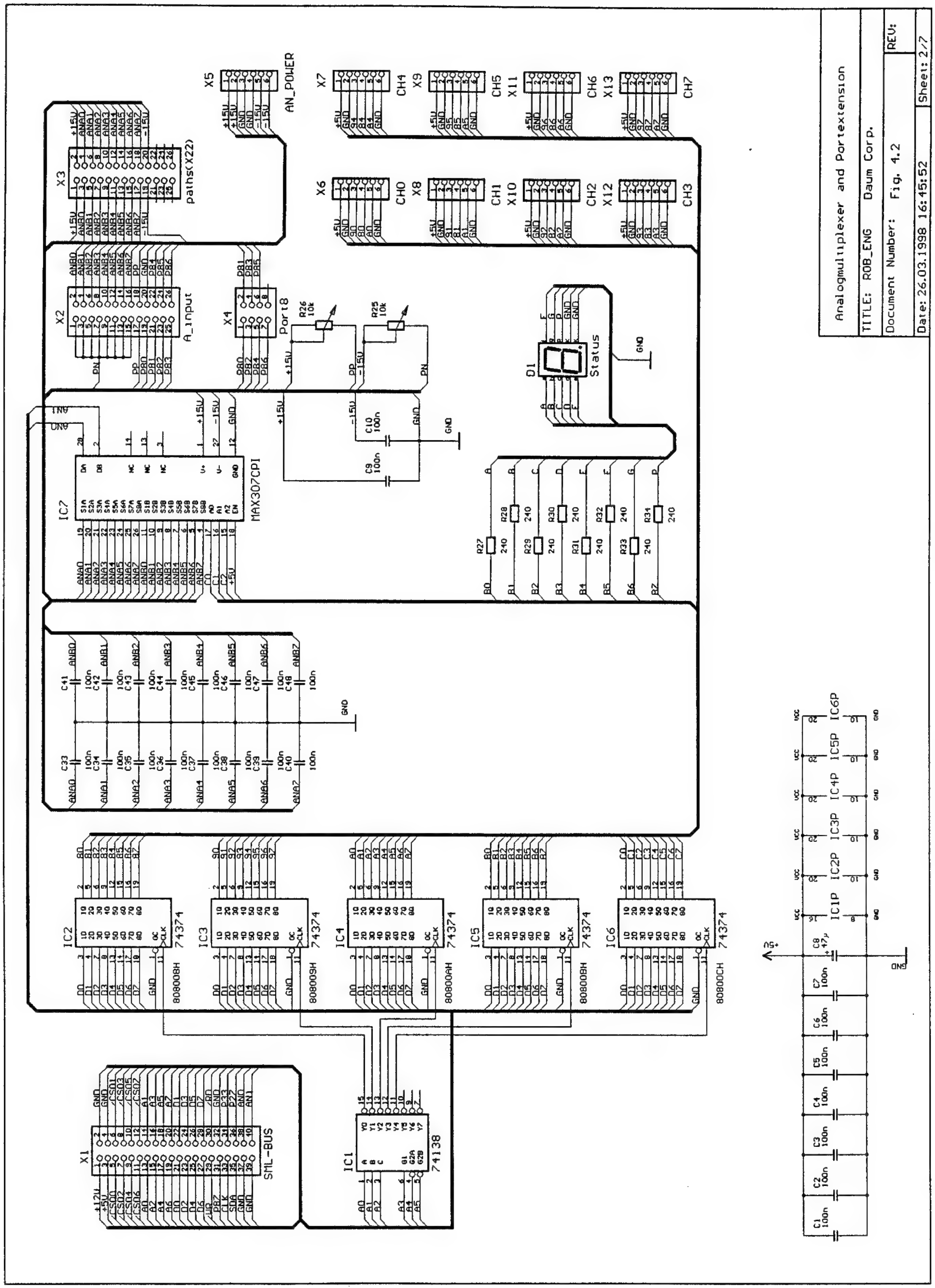
Sheet: 1/7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Daum Corp.
Document Number: Fig. 4.2
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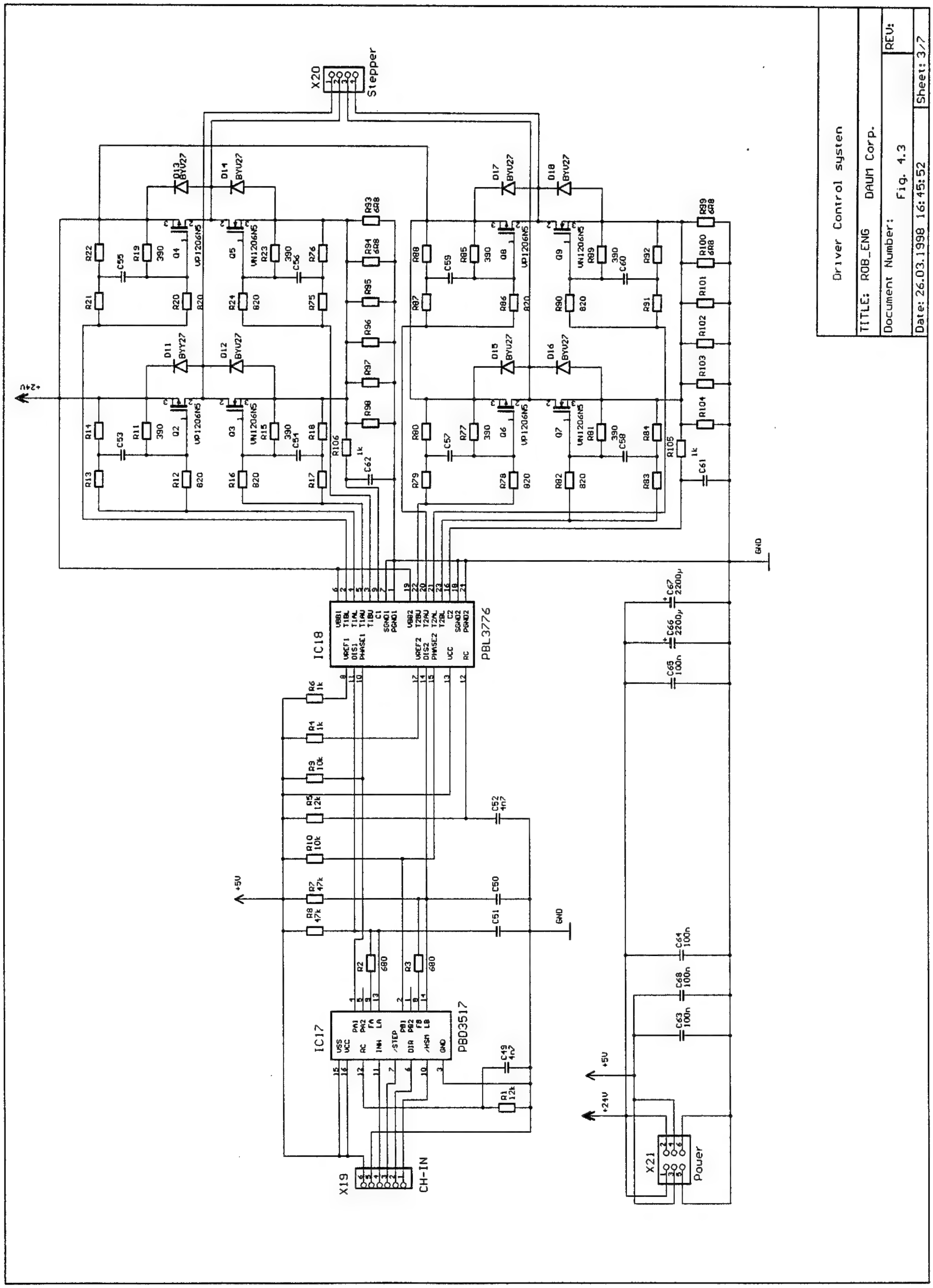
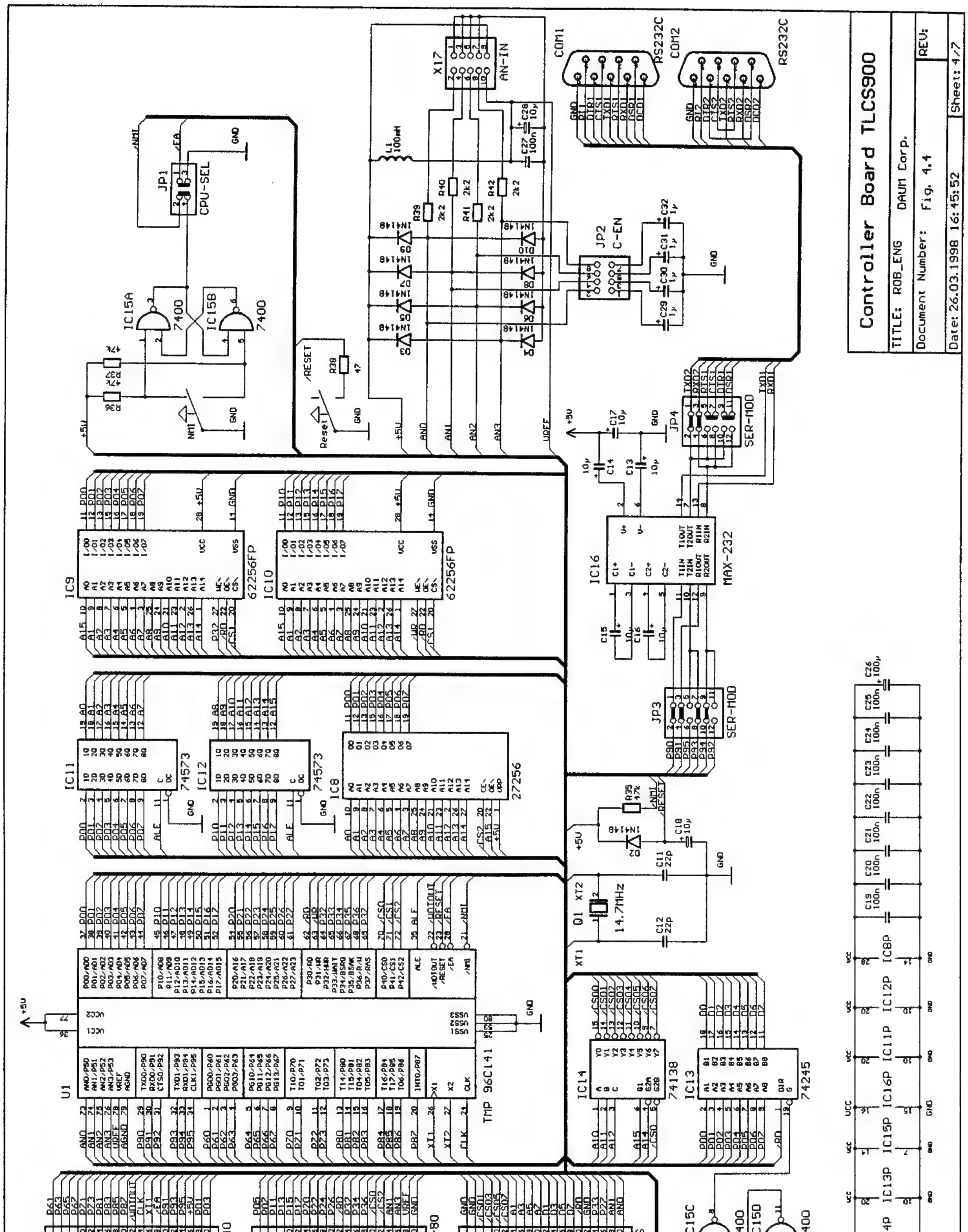
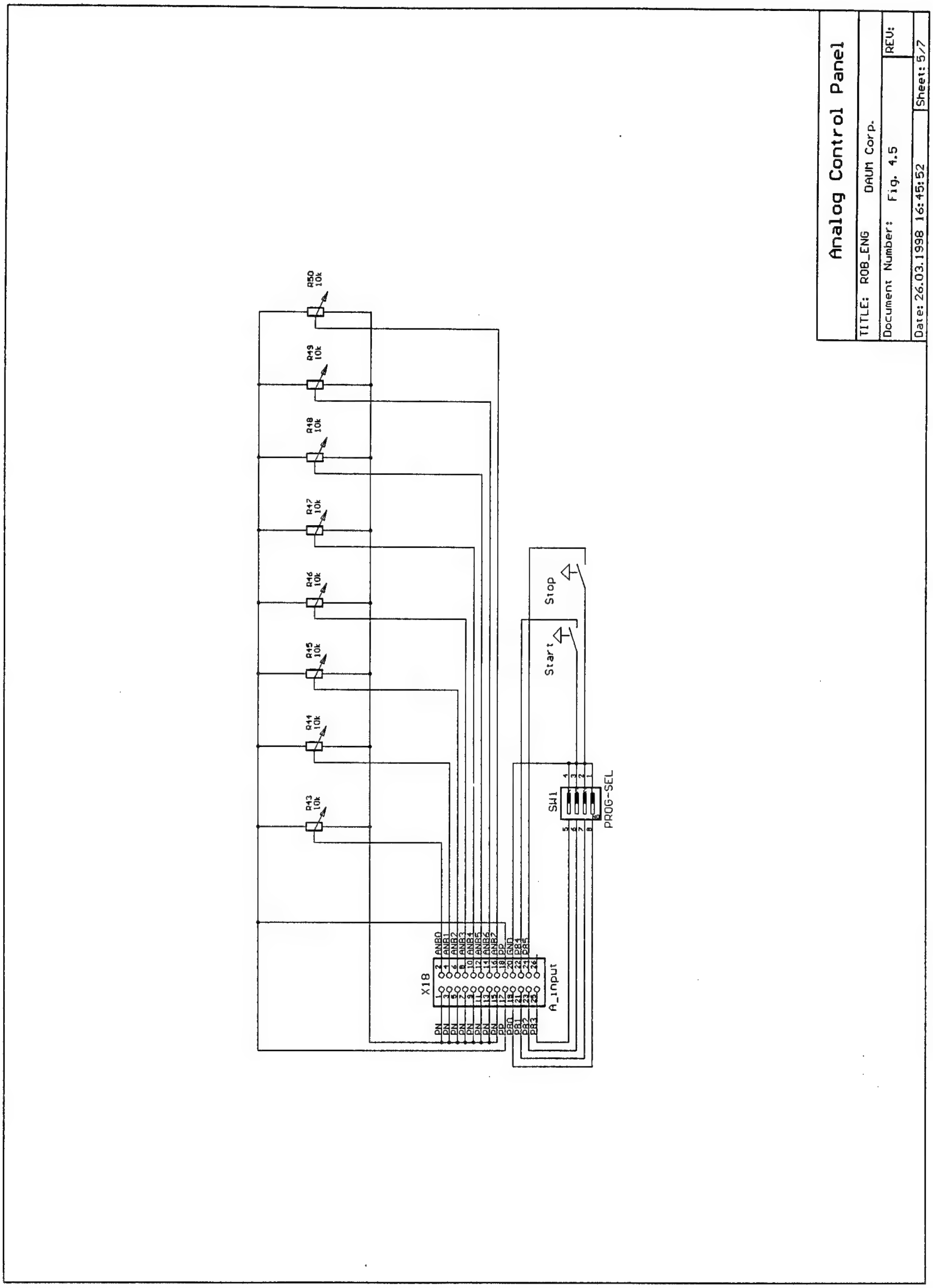


Daum Inc., Baltimore
DARPA Final Report for Grant Number
DAMD17-94-J-4502

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TITLE: ROB_ENG
DAUM Corp.
Document Number: Fig. 4.5
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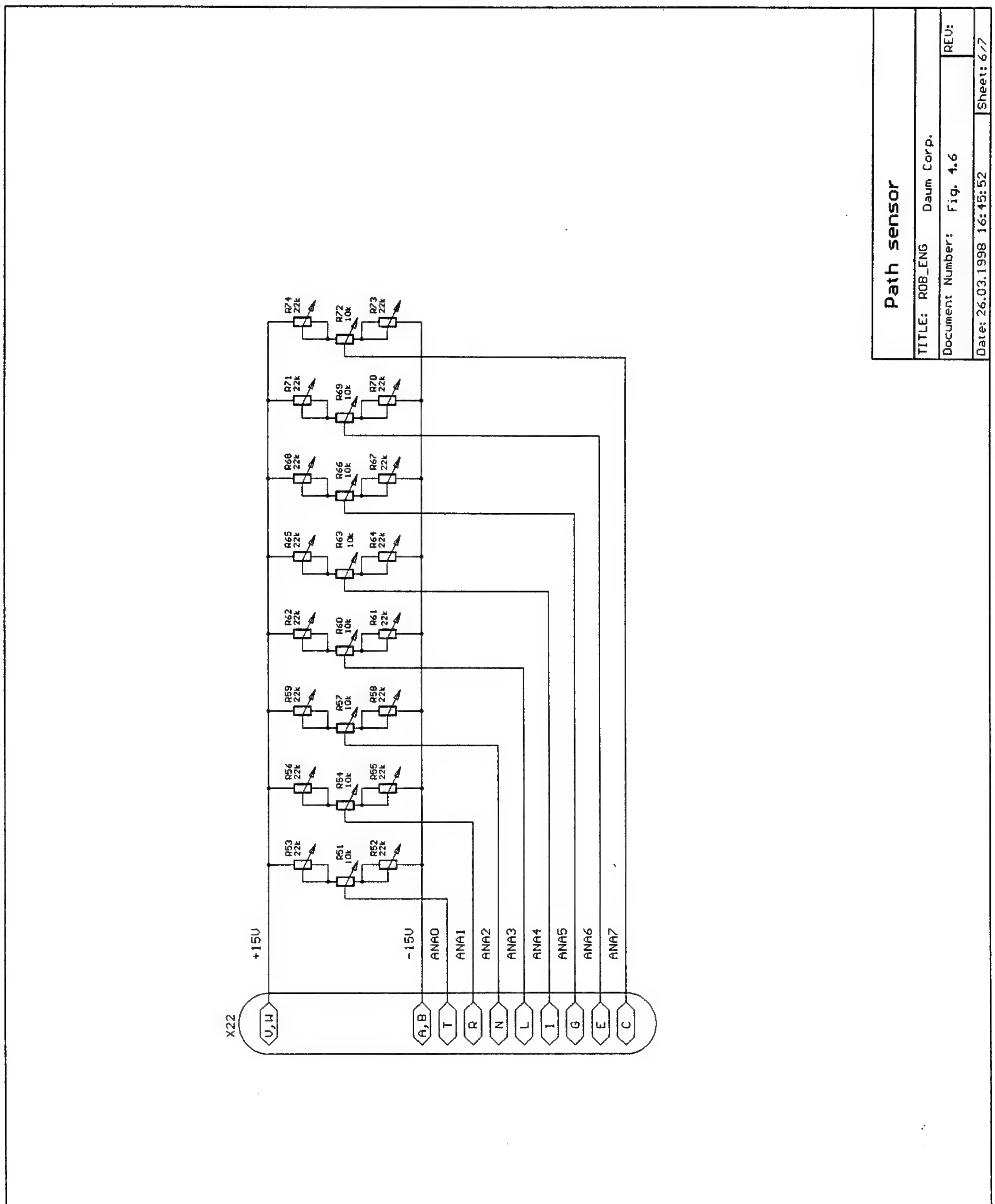
Date: 26.03.1998 16:45:52
Sheet: 5/7
R50 10k
R49 10k
R48 10k
R47 10k
R46 10k
R45 10k
R44 10k
R43 10k
Stop
Start
SW1
PROG-SEL
X18
A_input


Path sensor
TITLE: ROB_ENG
Daum Corp.
Document Number: Fig. 4.6
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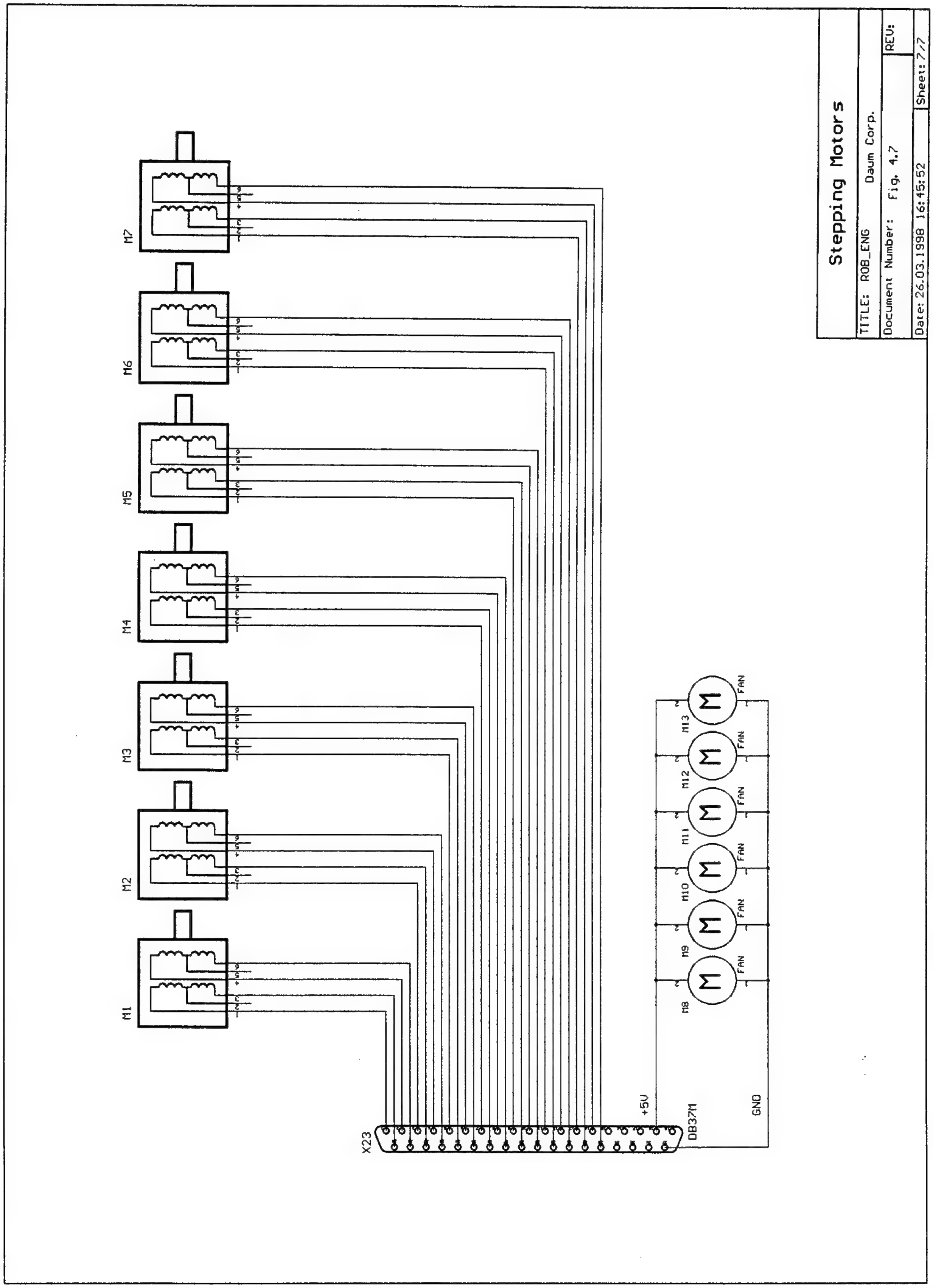
Date: 26.03.1998 16:45:52
Sheet: 6/7
X22
+15V
-15V
ANA0
ANA1
ANA2
ANA3
ANA4
ANA5
ANA6
ANA7


Stepping Motors
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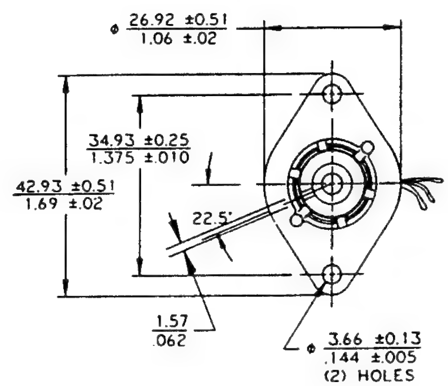
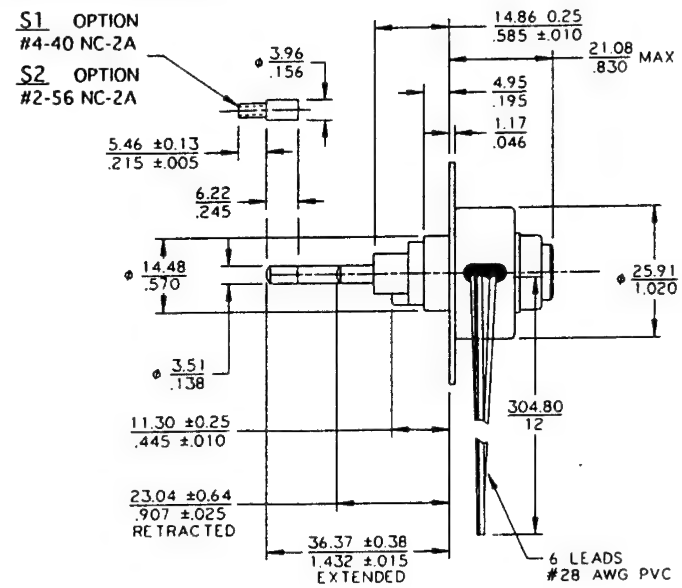
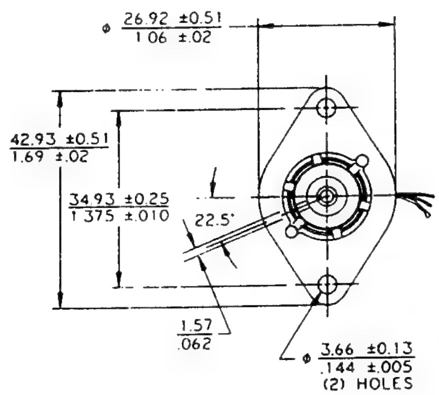
Sheet: 7/7
M1
M2
M3
M4
M5
M6
M7
M8
M9
M10
M11
M12
M13
FAN
+5V
GND
X23
DB37M

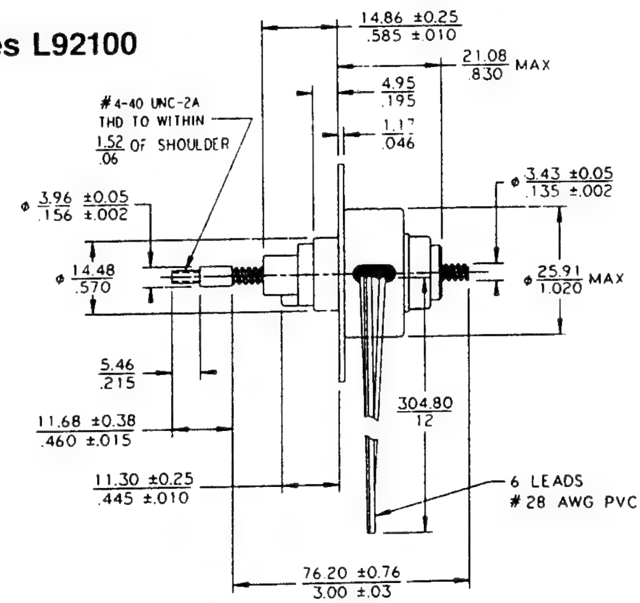
Series K92100



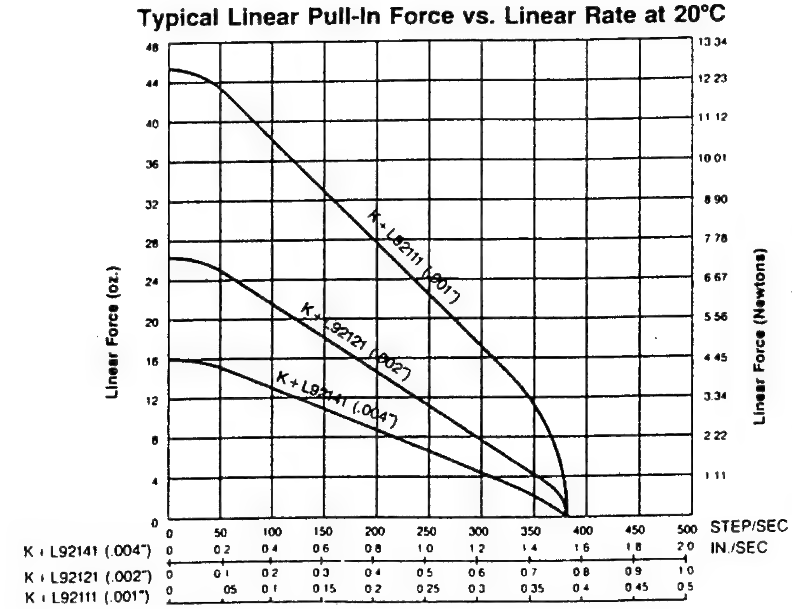


Series L92100





Typical Linear Pull-In Force vs. Linear Rate at 20°C



Dimensional Drawings

(mm/inches)
UNSPECIFIED TOL. ± $\frac{.127}{.005}$

Fig. 4.8

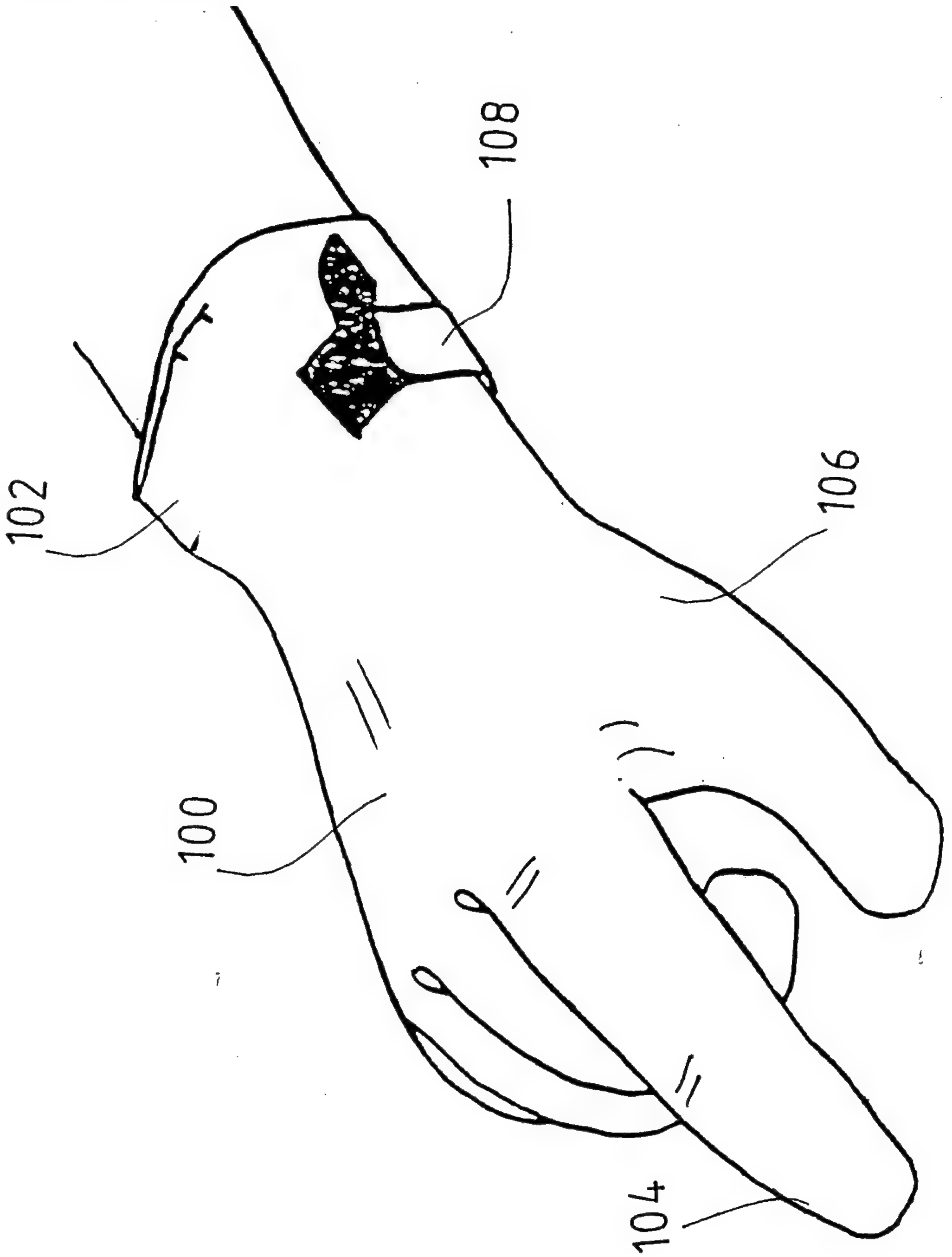


Fig. 5.1

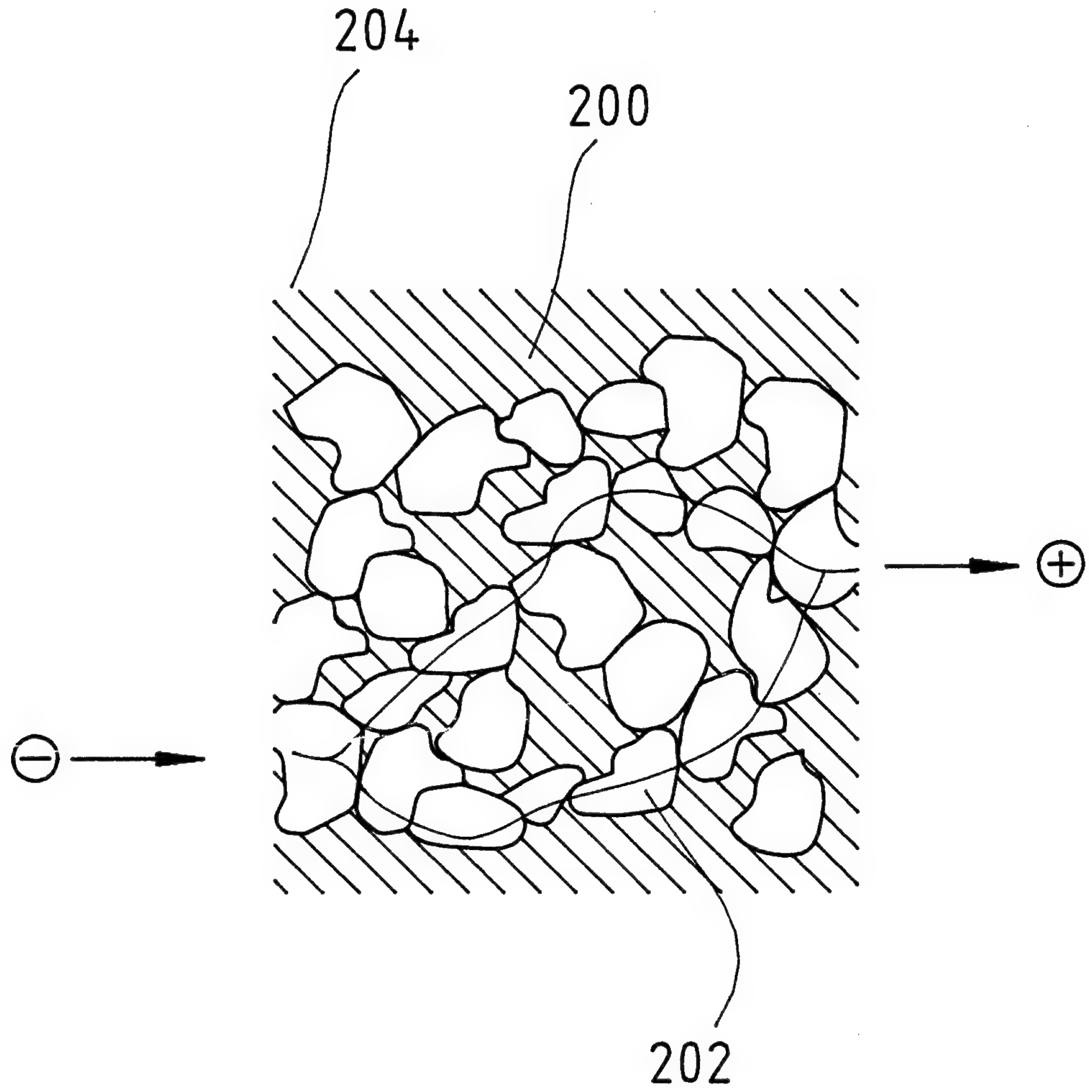


Fig. 5.2

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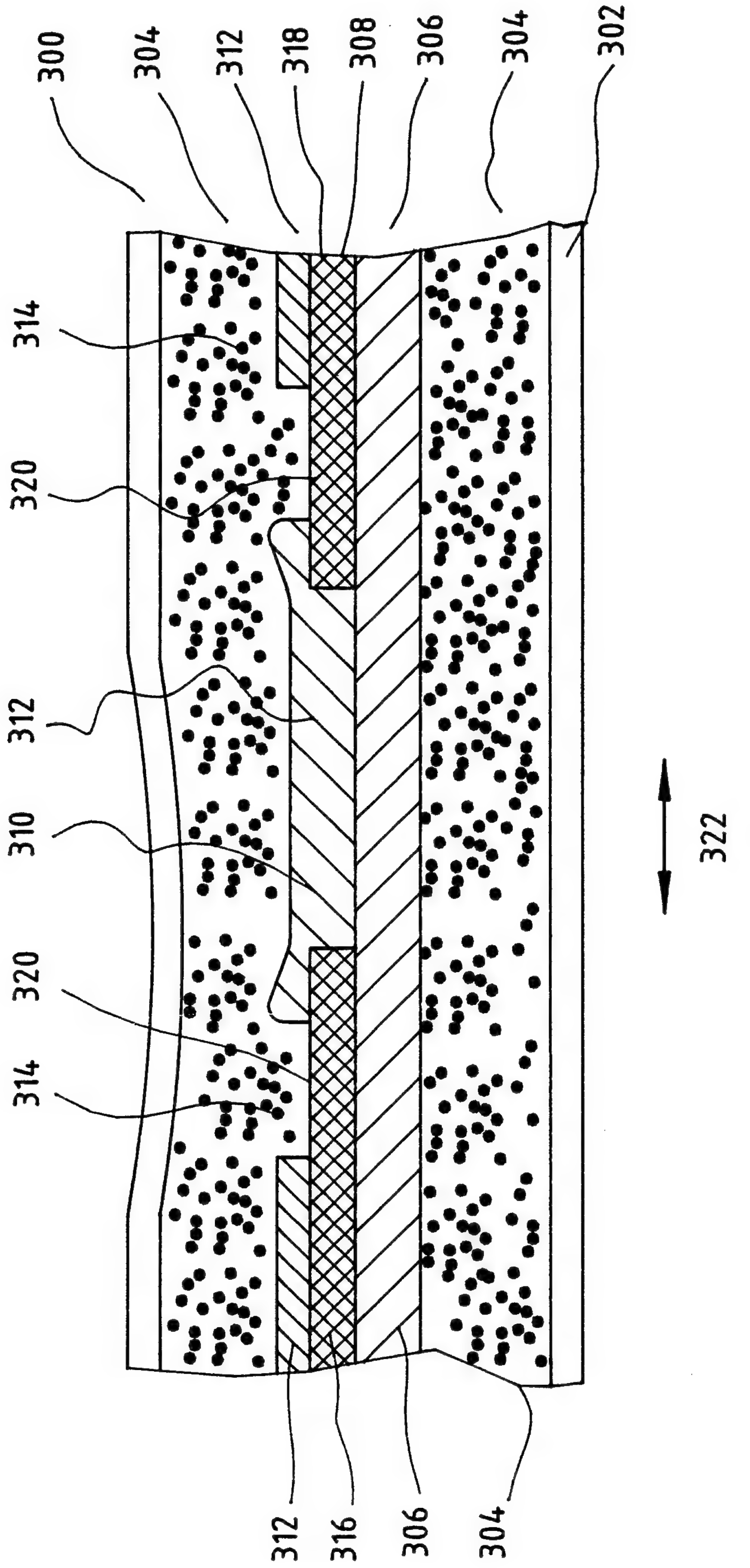

Fig. 5.3.a

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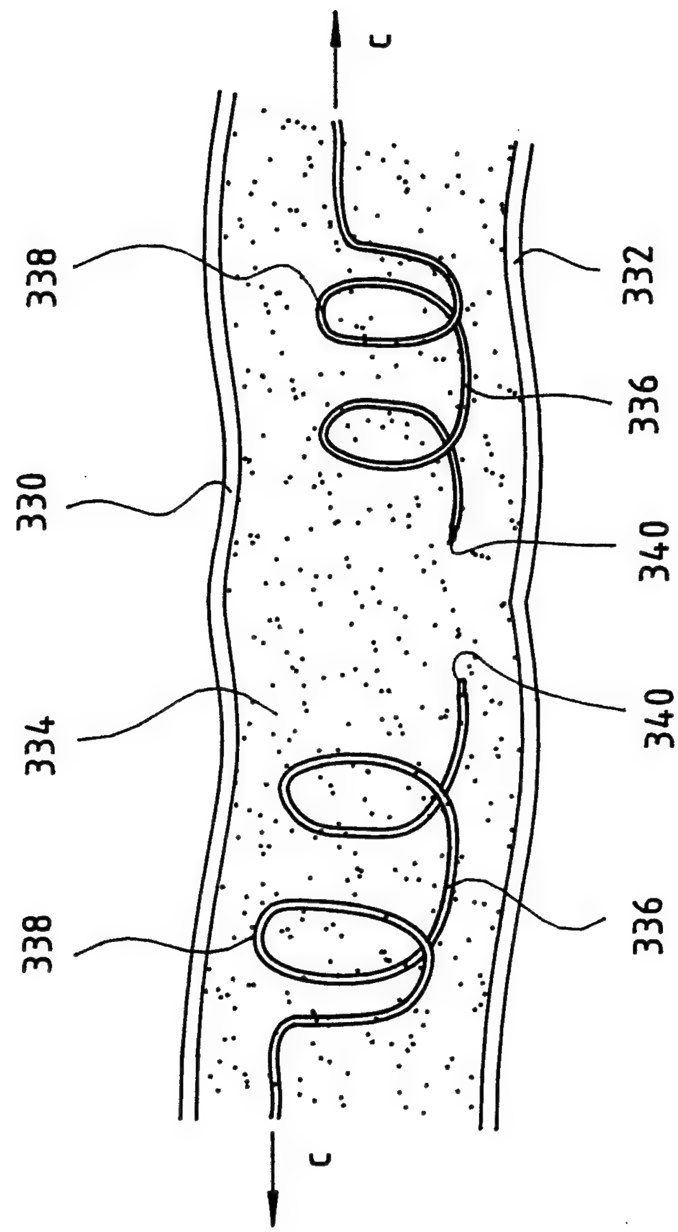

Fig. 5.3.b

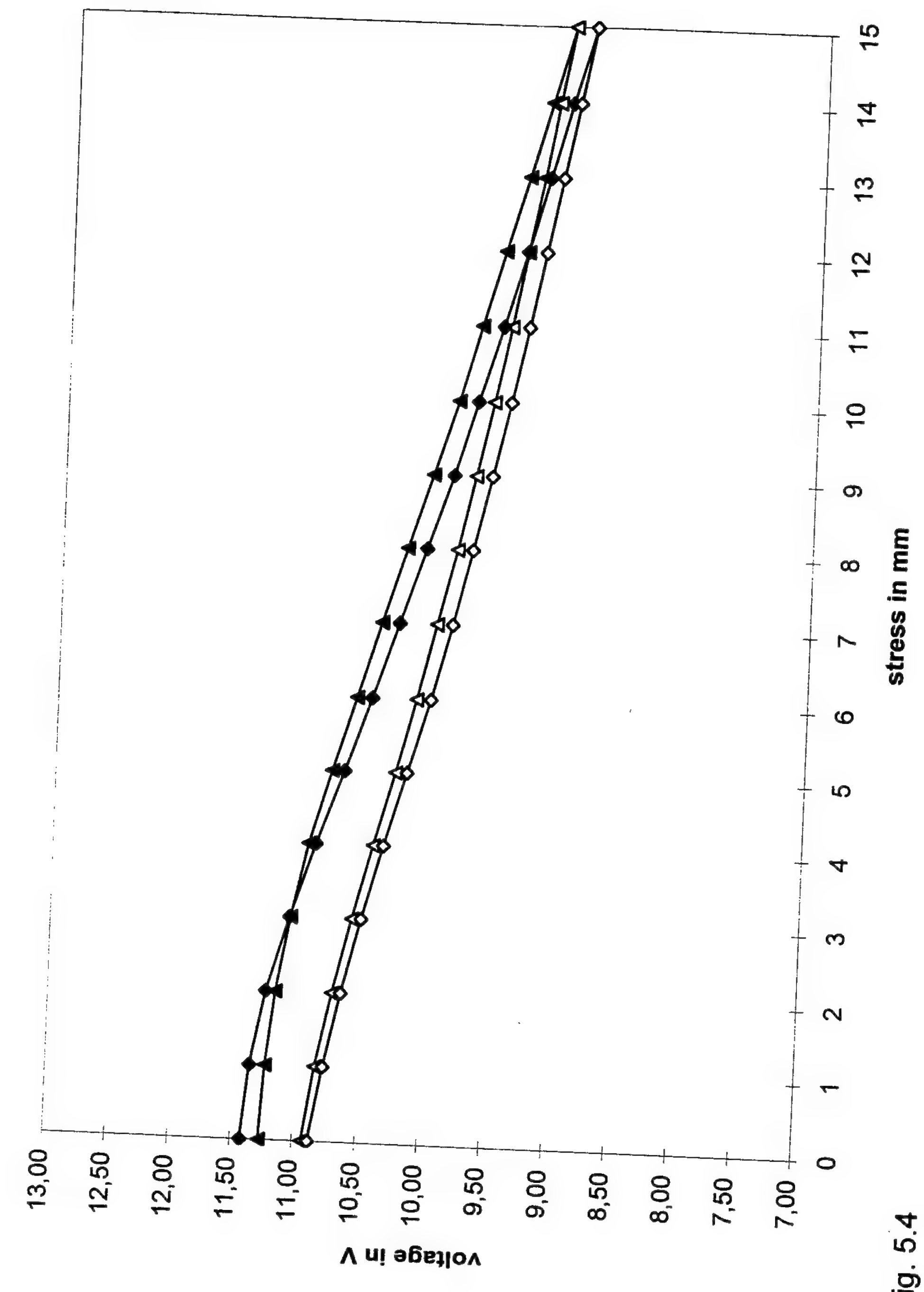
voltage in V
13,00
12,50
12,00
11,50
11,00
10,50
10,00
9,50
9,00
8,50
8,00
7,50
7,00
stress in mm
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Fig. 5.4

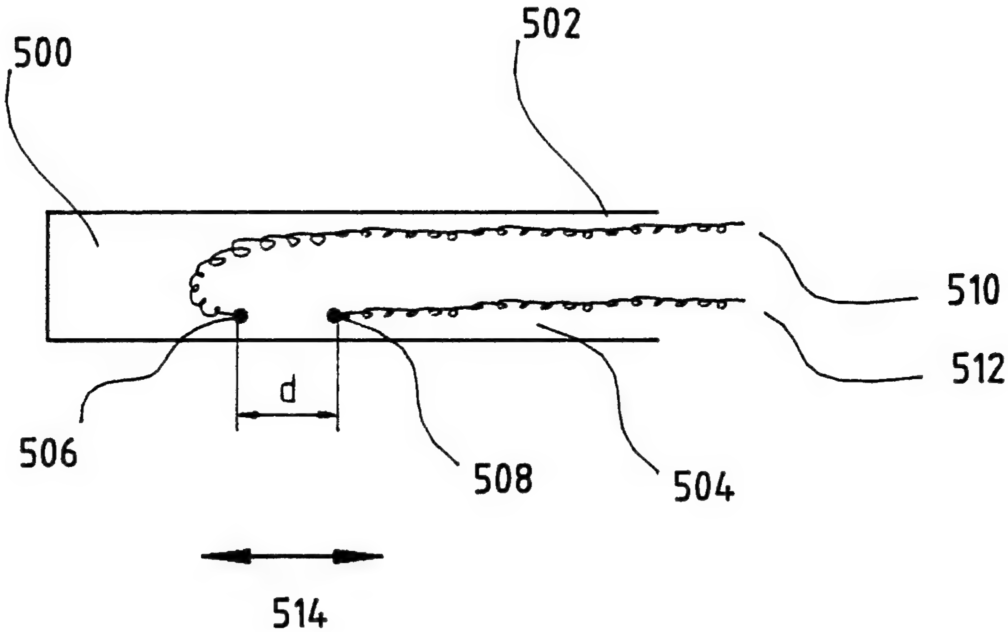

Fig. 5.5.a

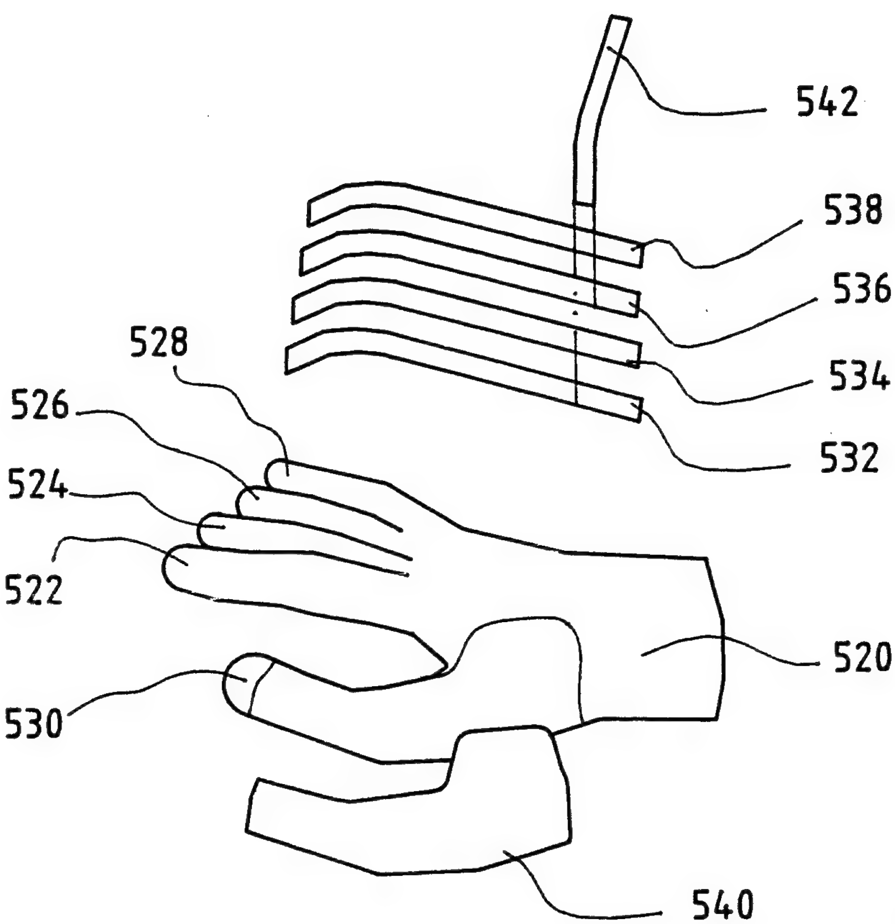

Fig. 5.5.b

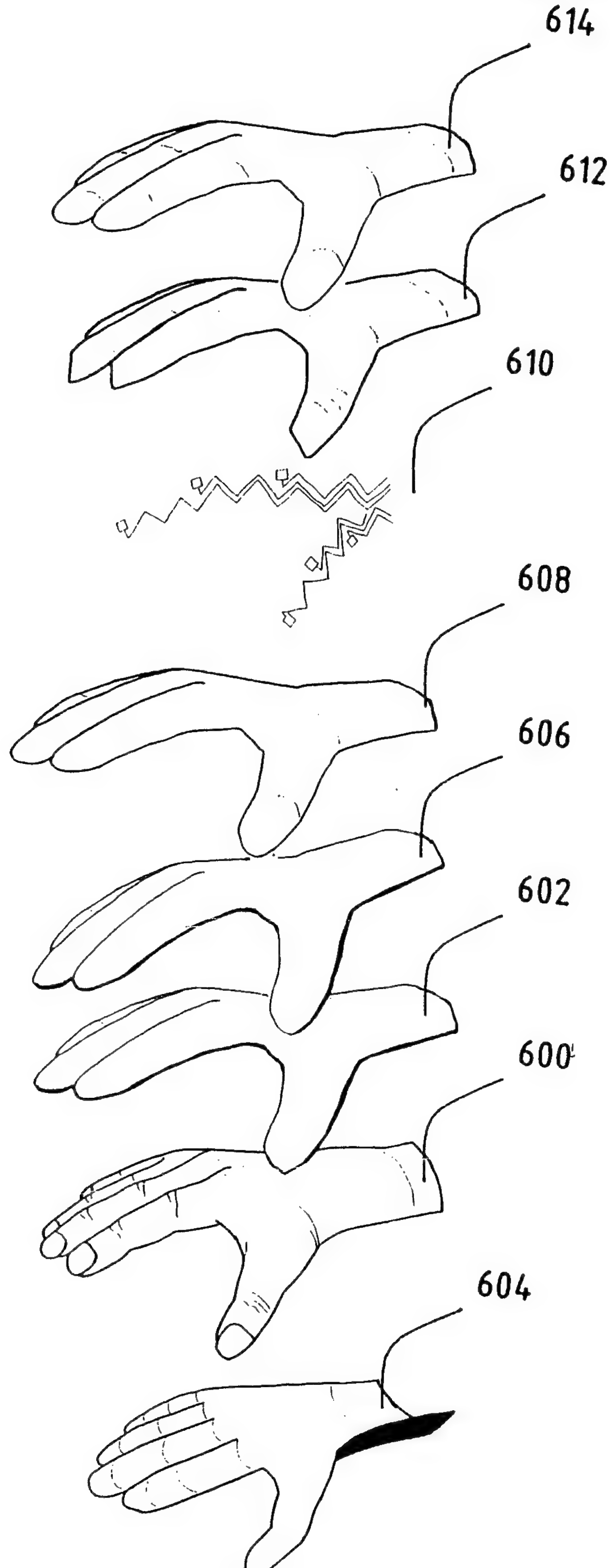

Fig. 5.6

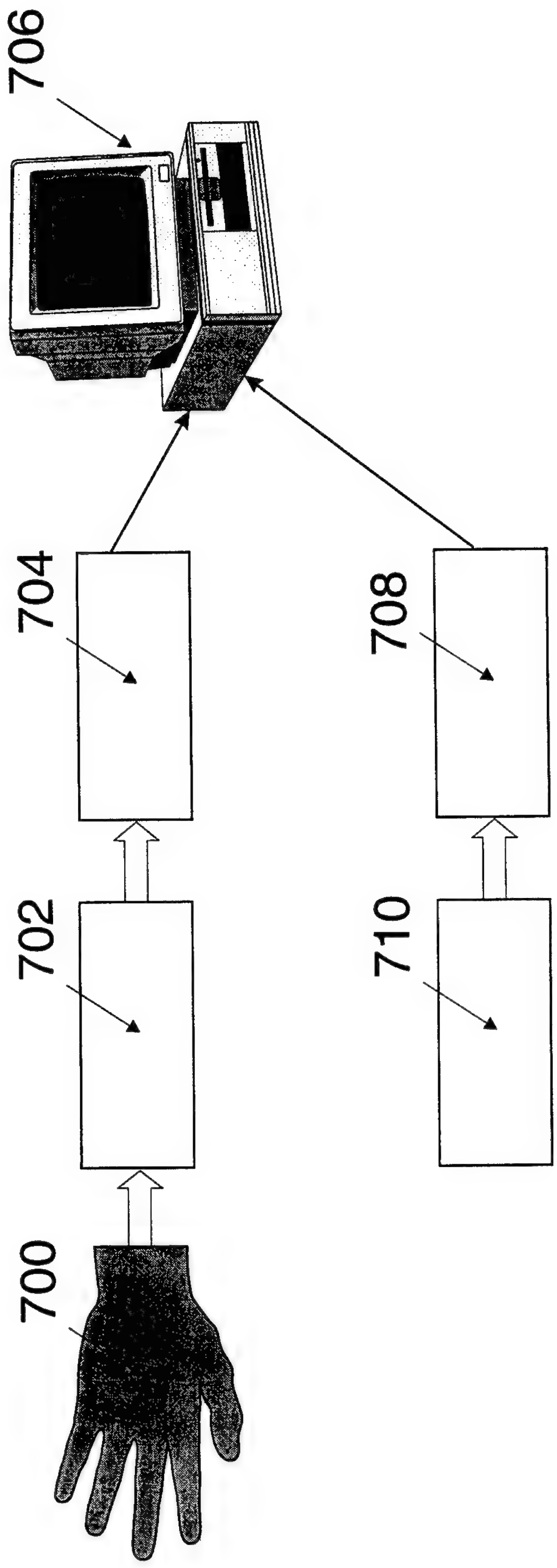

Fig. 5.7

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21 degrees of freedom of fingers

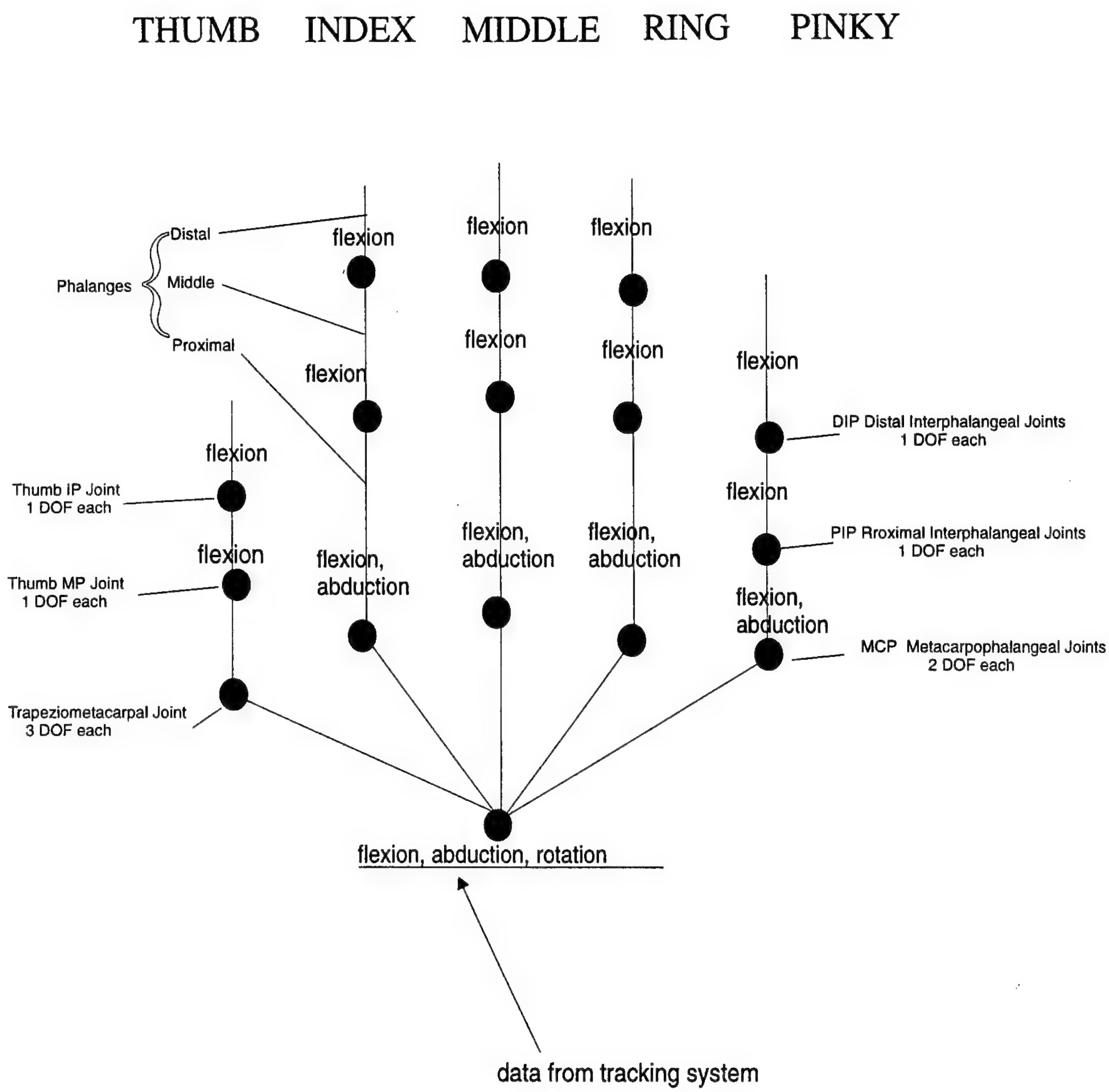

Fig. 5.8

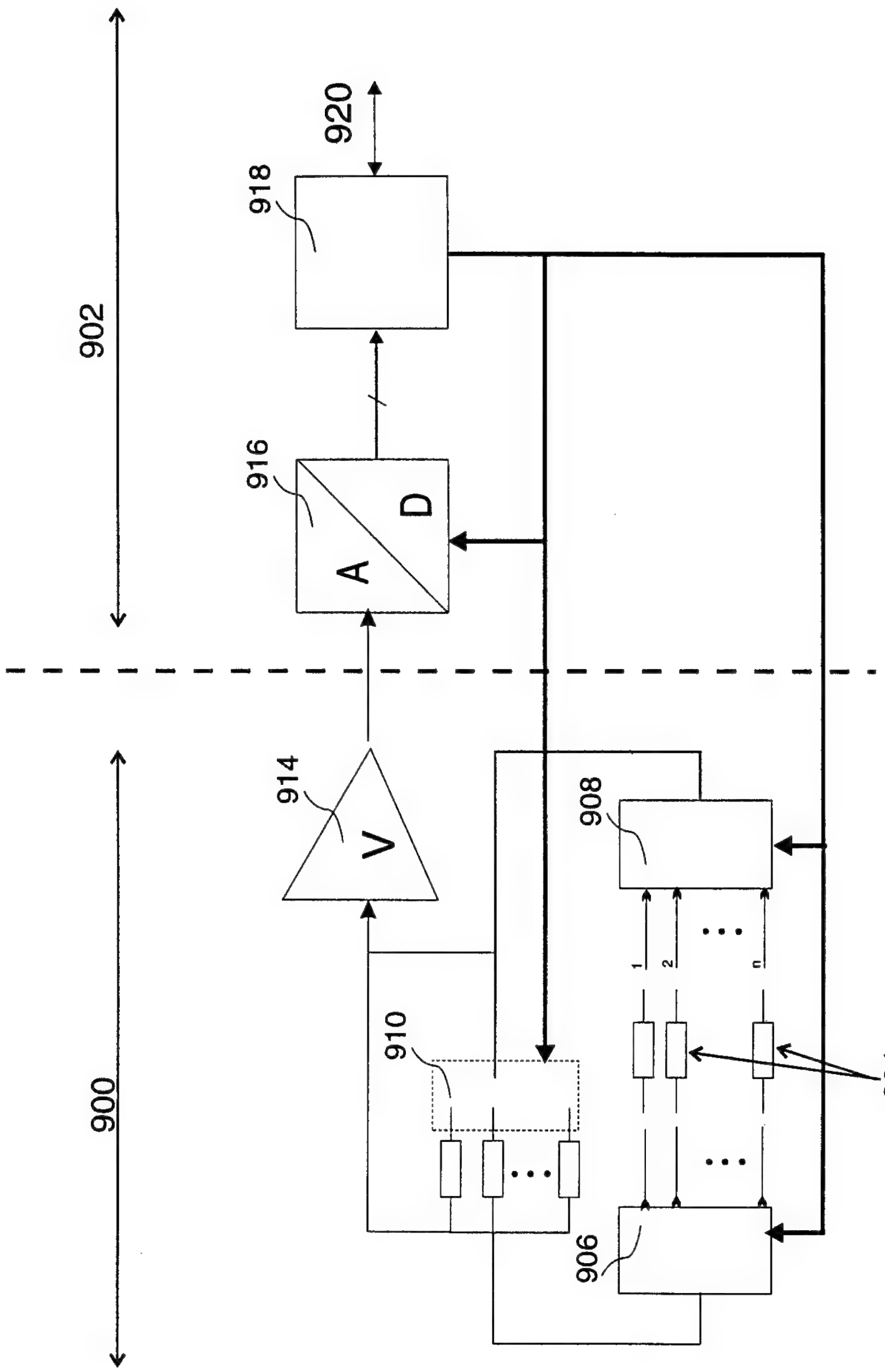

Fig. 5.9

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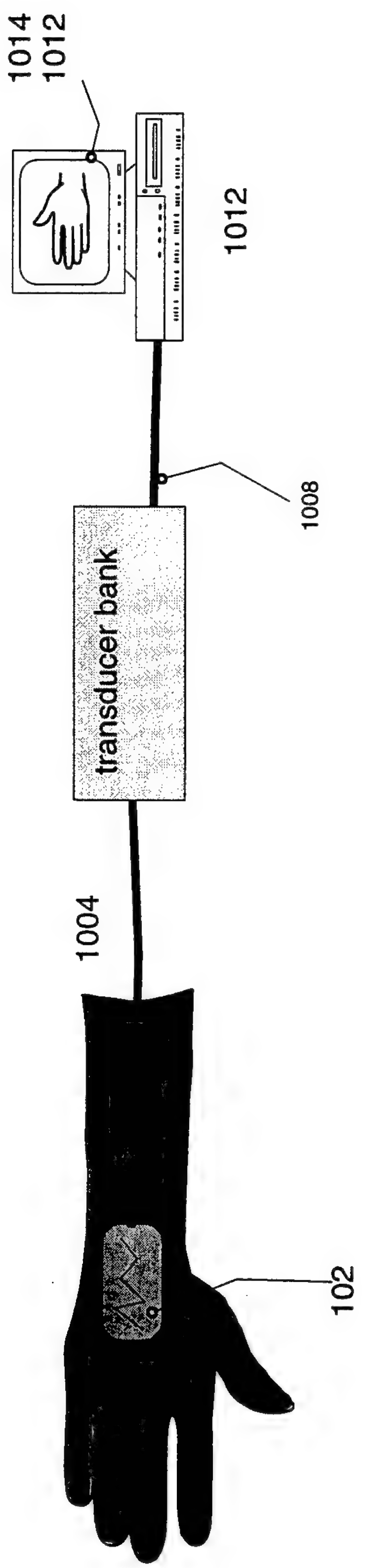
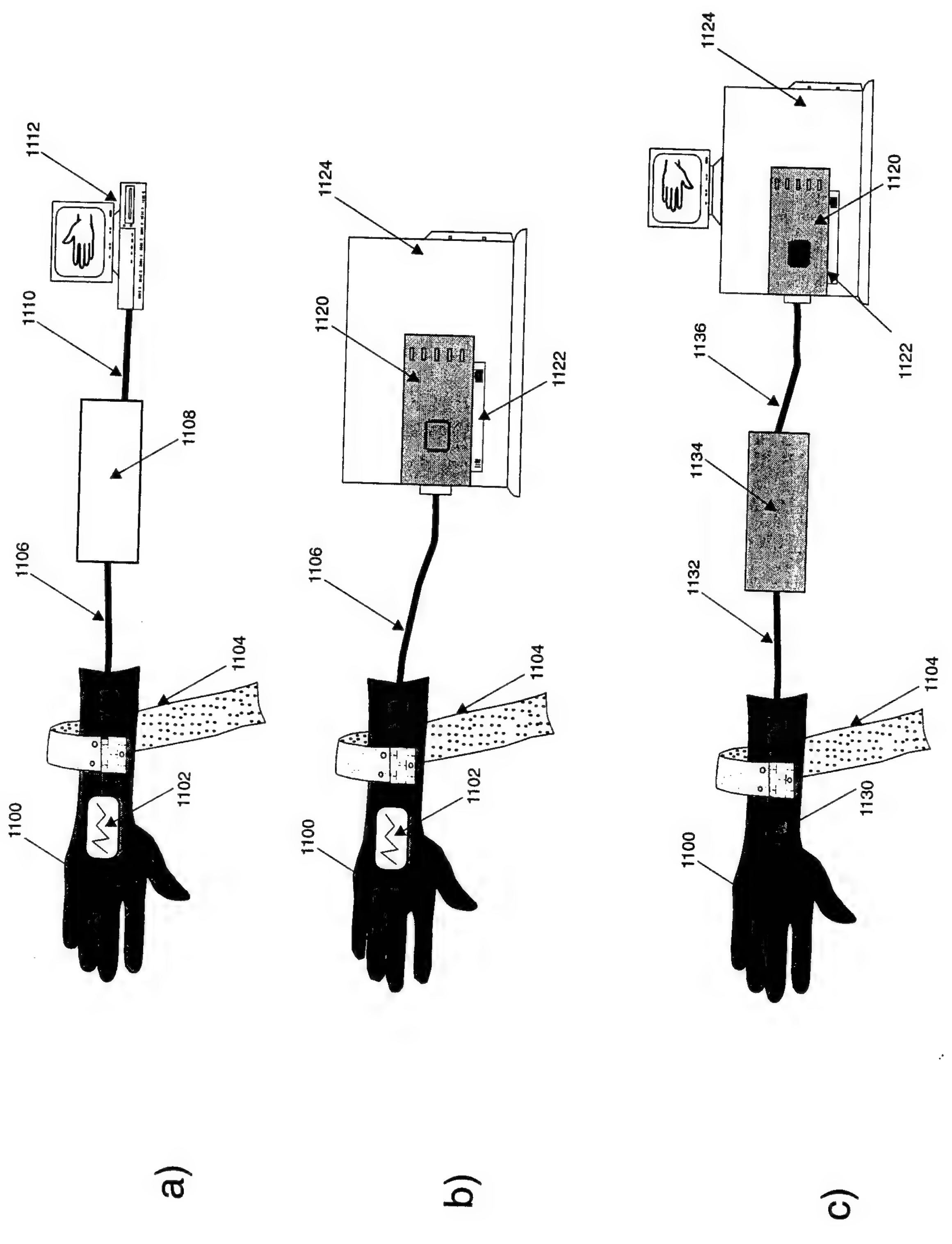


Fig. 5.10


a)
1100
1102
1104
1106
1108
1110
1112
b)
1100
1102
1104
1106
1120
1122
1124
c)
1100
1130
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1132
1134
1136
1120
1122
1124

Fig. 5.11

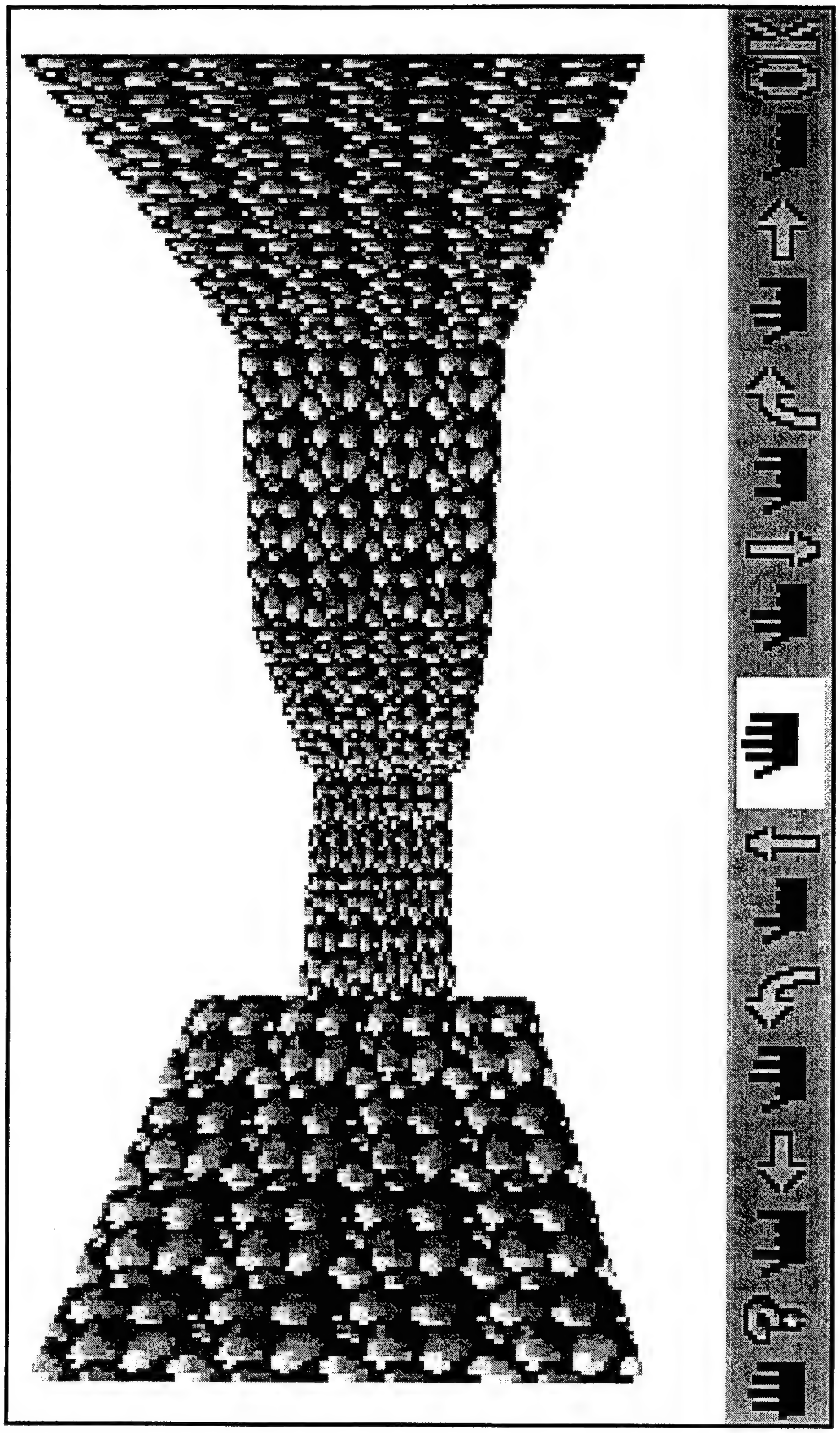
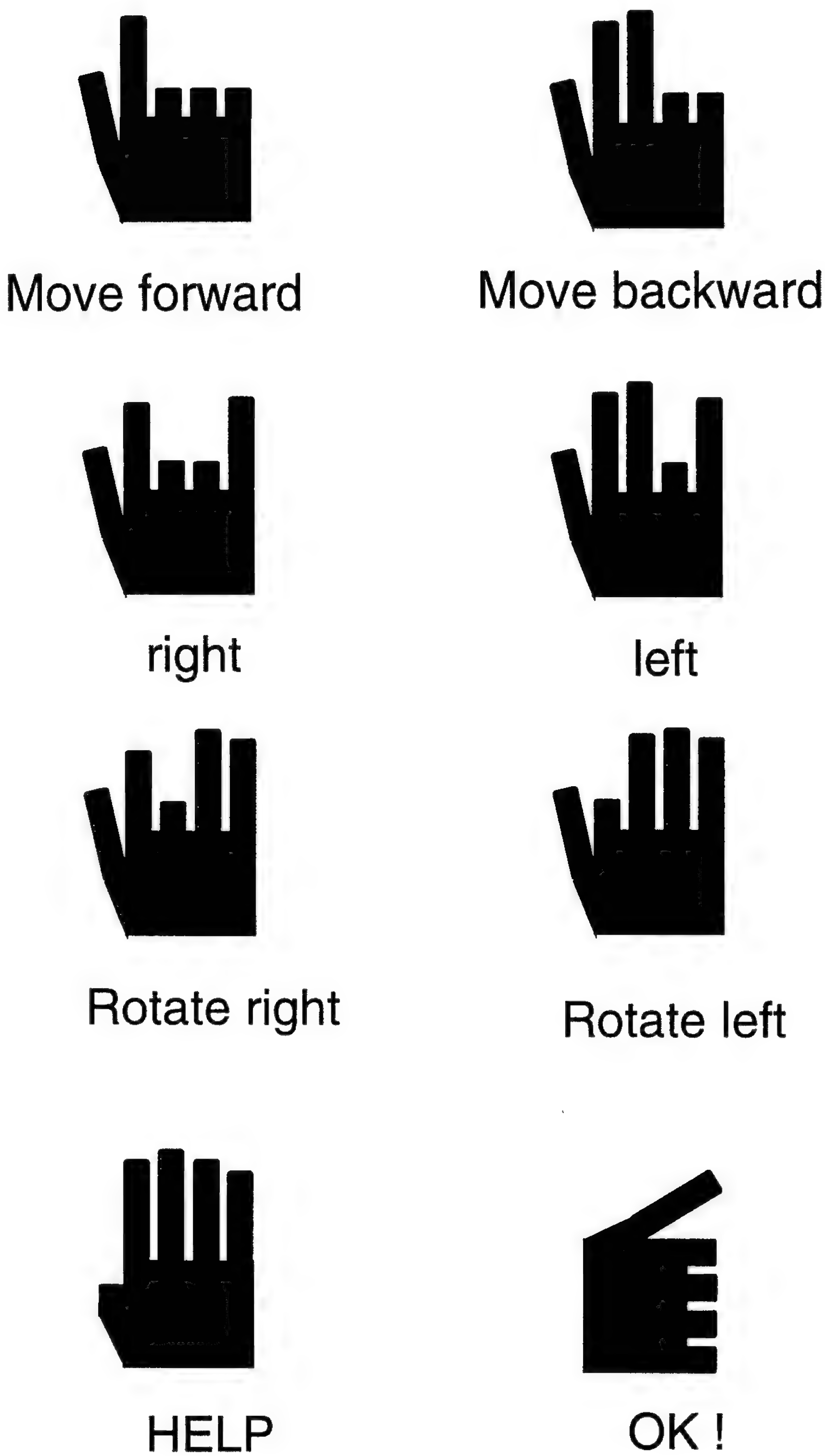


Fig. 5.12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Move backward
right
left
Rotate right
Rotate left
HELP
OK !

Fig. 5.13

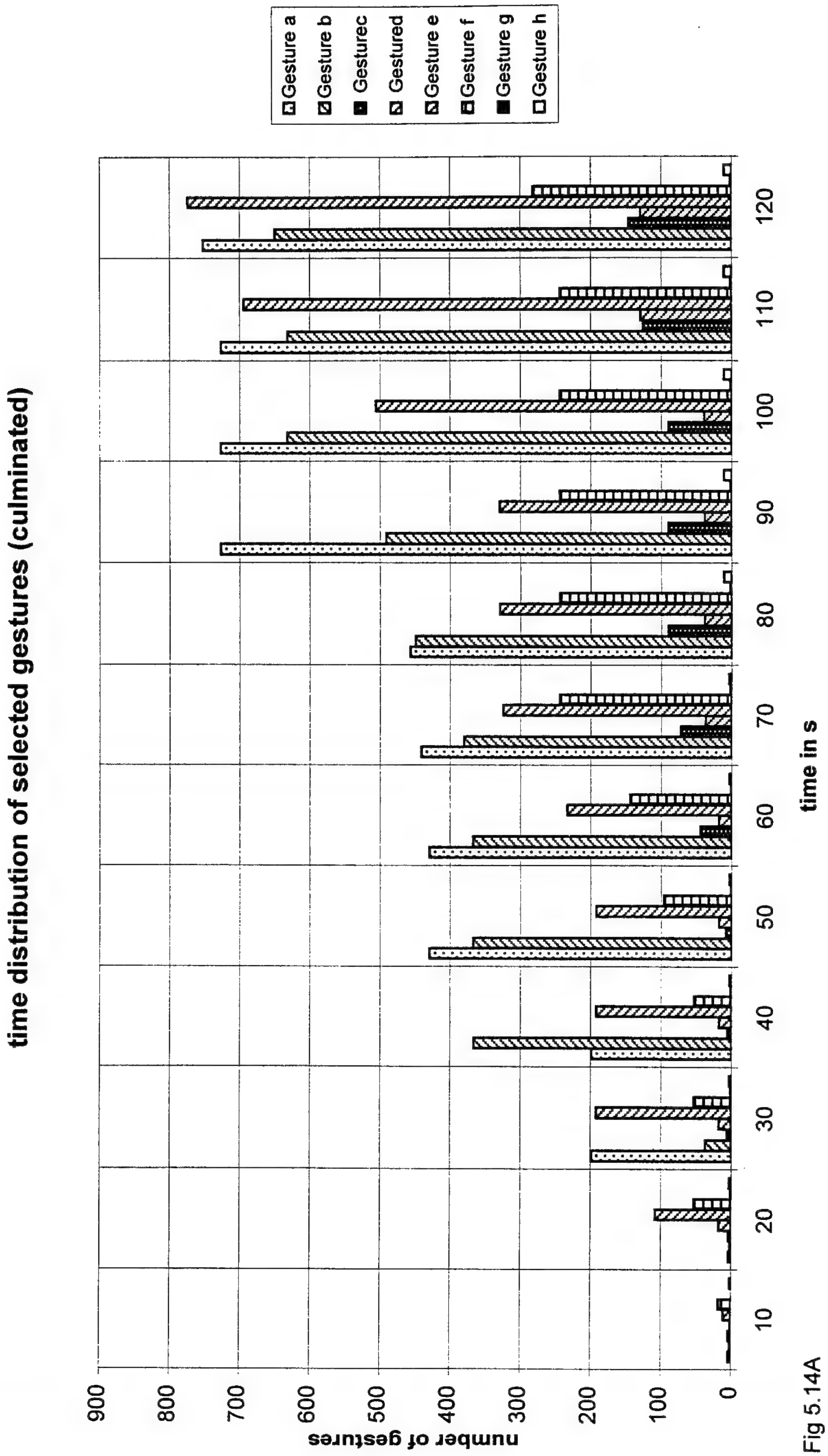

time distribution of selected gestures (culminated)
Gesture a
Gesture b
Gesturec
Gestured
Gesture e
Gesture f
Gesture g
Gesture h
number of gestures
0
100
200
300
400
500
600
700
800
900
time in s
10
20
30
40
50
60
70
80
90
100
110
120

Fig 5.14A

DAUM®

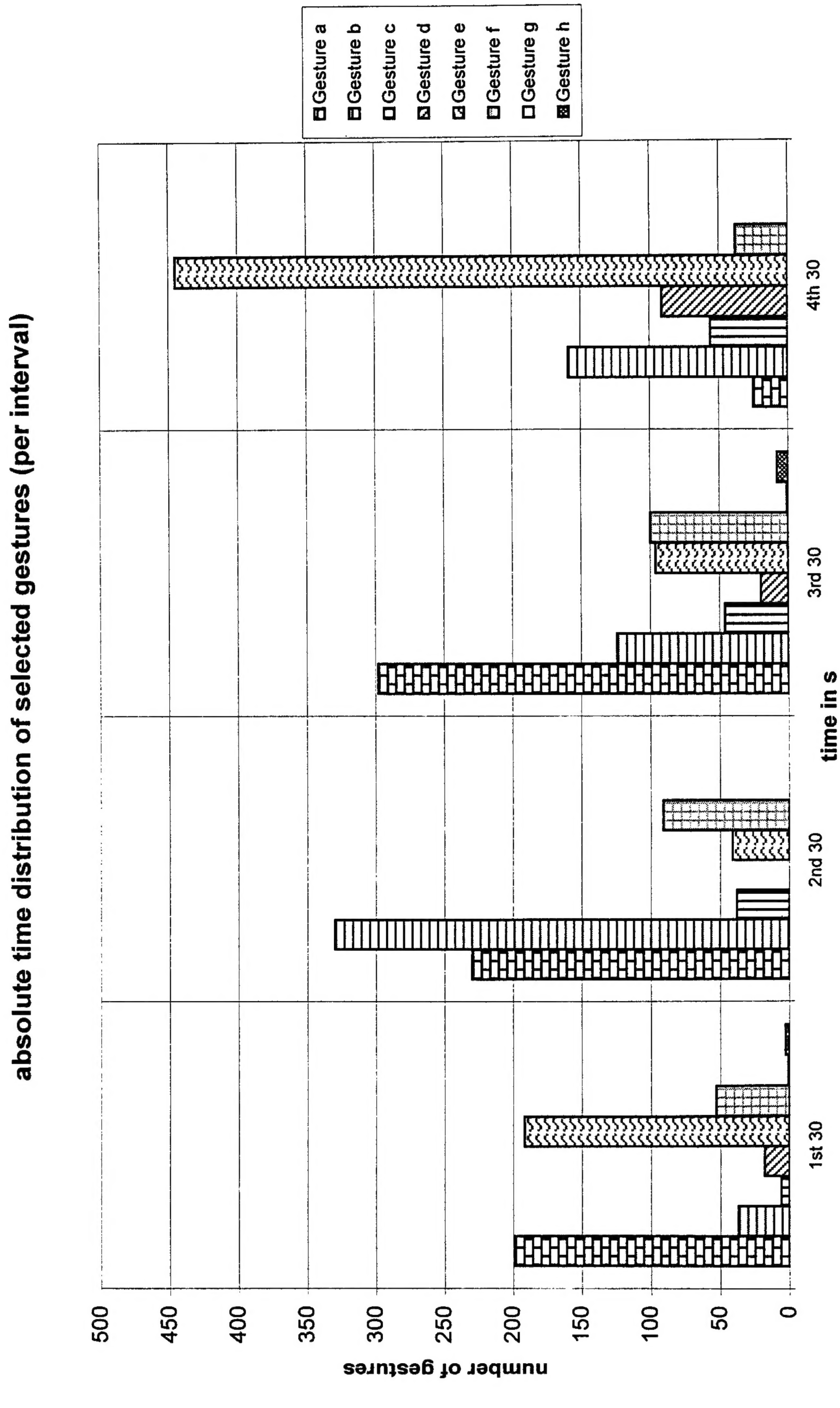


Fig. 5.14 B

DAUM®

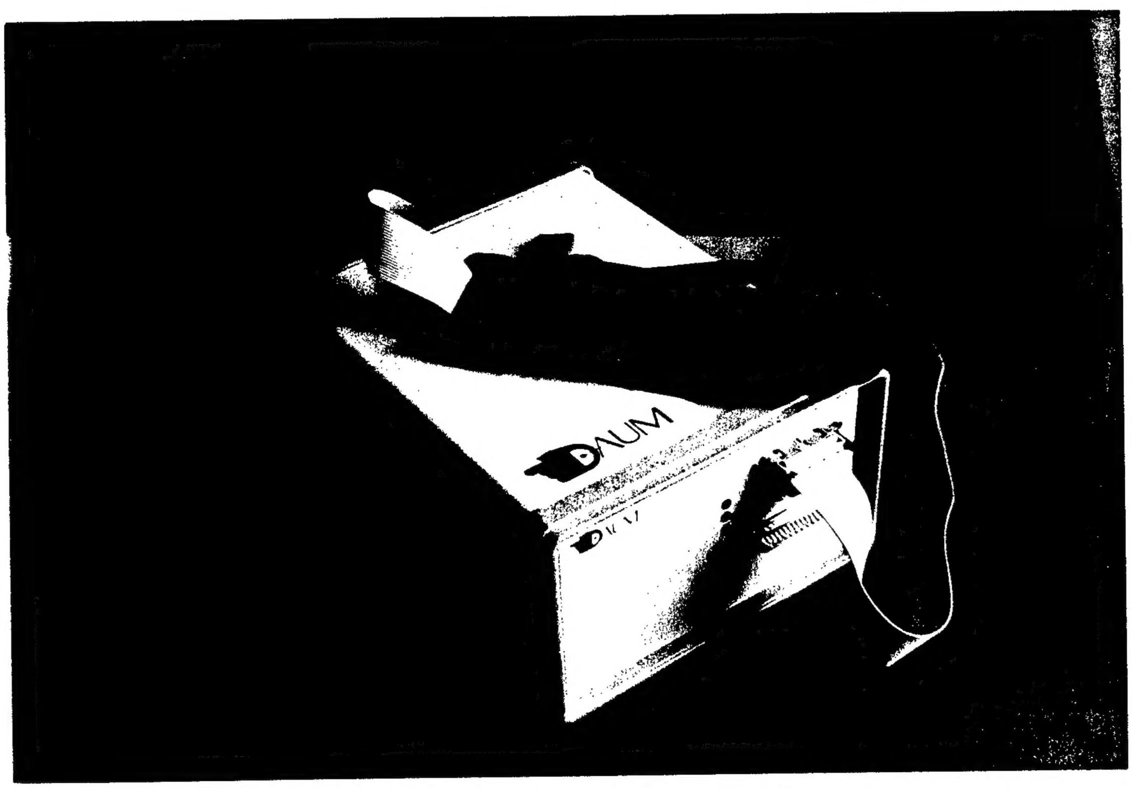
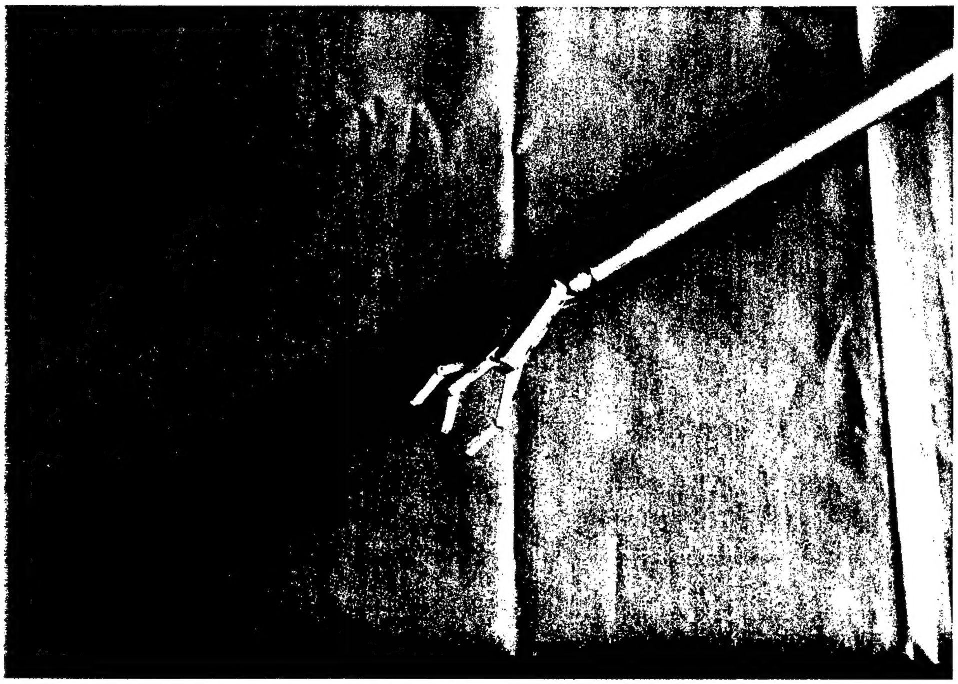


Fig. 6.1.a



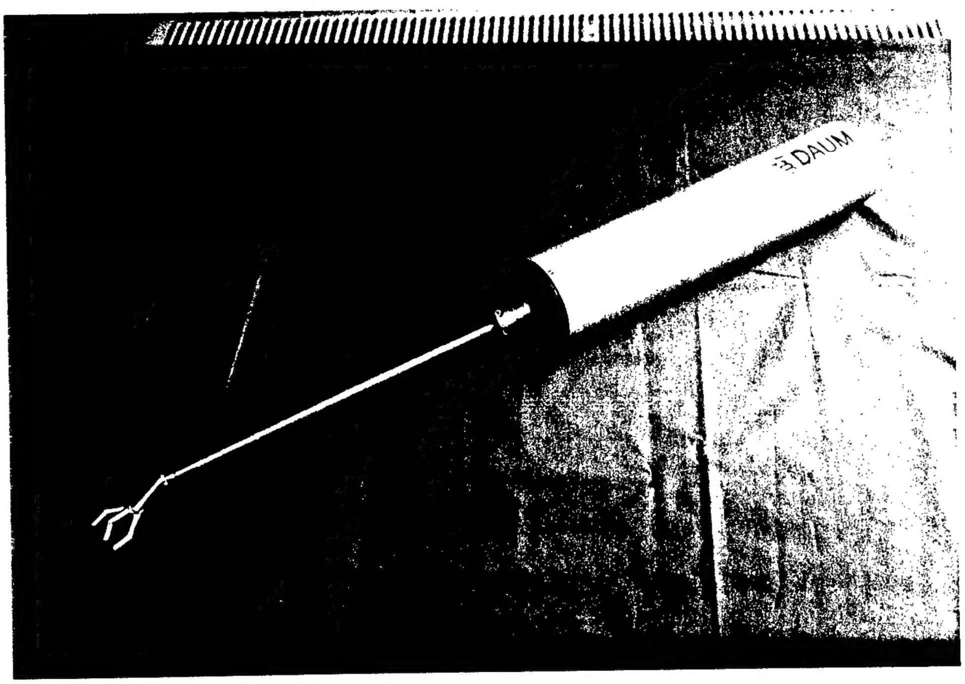


Fig. 6.1.b

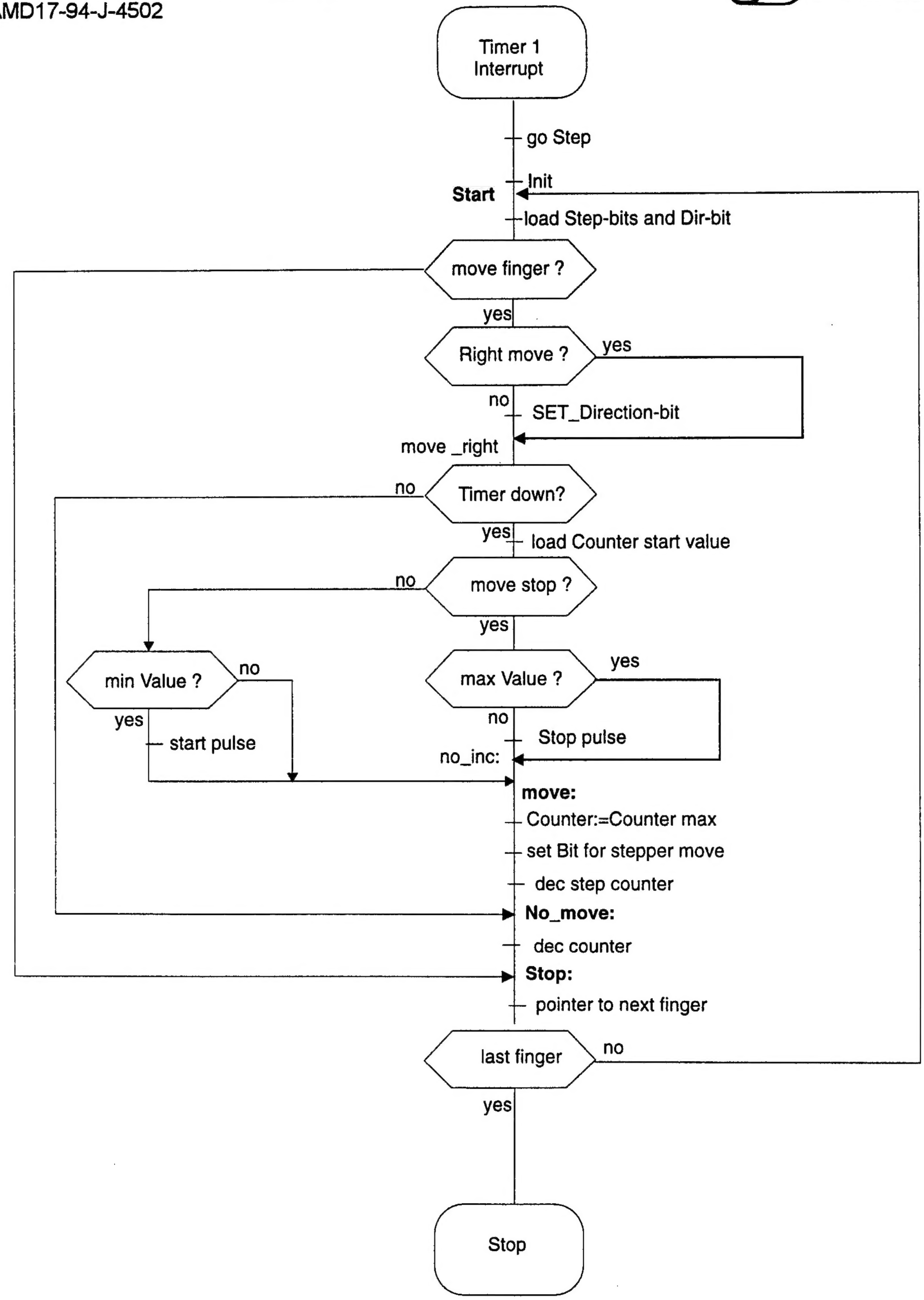

Timer 1 Interrupt
go Step
Init
Start
load Step-bits and Dir-bit
move finger ?
yes
Right move ?
yes
no
SET_Direction-bit
move _right
no
Timer down?
yes
load Counter start value
no
move stop ?
yes
min Value ?
no
yes
start pulse
max Value ?
yes
no
Stop pulse
no_inc:
move:
Counter:=Counter max
set Bit for stepper move
dec step counter
No_move:
dec counter
Stop:
pointer to next finger
last finger
no
yes
Stop

Fig. 7.1